A BOTTOM GRAVITY SURVEY OF THE SHALLOW WATER REGIONS OF SOUTHERN MONTEREY BAY AND ITS GEOLOGICAL INTERPRETATION

Robert Andrew Brooks

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

A BOTTOM GRAVITY SURVEY OF THE SHALLOW WATER REGIONS OF SOUTHERN MONTEREY BAY AND ITS GEOLOGICAL INTERPRETATION

by

Robert Andrew Brooks, Sr.

Advisors: Robert S. Andrews
J. J. von Schwind

March 1973

A Bottom Gravity Survey of the Shallow Water Regions of Southern Monterey Bay and Its Geological Interpretation

by

Robert Andrew Brooks, Sr.
Lieutenant, United States Navy
B.S., United States Naval Academy, 1966

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
March 1973

ABSTRACT

Eighty-two ocean bottom gravity stations in southern Monterey Bay were occupied in the summer and fall of 1972 from the R/V ACANIA. A land gravity survey of ten stations about the perimeter of the Bay was conducted in the spring of 1972. Gravimeters employed were LaCoste and Romberg Models H6G and G-17B, respectively.

Conventional steps in data reduction are discussed, and a terrain correction theory unique to ocean bottom gravimetry is presented. The complete Bouguer anomaly (CBA) field for bottom and shoreline surveys is included.

The geological interpretation of the gravity data is discussed briefly. Sub-bottom structure of southern Monterey Bay as determined by seismic reflection is verified by the CBA field, and a calculated density contrast between the basement granodiorite and overlying sedimentary strata is found to be realistic. The data supports the existence of a fault oriented beneath the Monterey Submarine Canyon.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

BC - Total Bouguer Correction

BC_1 - Attractive Force per Unit Mass of Overlying Water

BC_2 - Attractive Force per Unit Mass of Underlying Water

BC_3 - Attractive Force per Unit Mass due to Rock vice Water in Underlying Layer

CBA - Complete Bouguer Anomaly

CC - Curvature Correction

CV_o - Observed Counter Value

D - Drift Correction

$\frac{dg_n}{dz}$ - Vertical Gradient of Newtonian Gravity

ET - Earth Tide Correction

FAA - Free-Air Anomaly

FAA' - "Mass-Adjusted" Free-Air Anomaly

FAC - Free-Air Correction

G - Universal Gravitational Constant

g_n - Newtonian Gravity

g_o - Observed Gravity

g_t - Theoretical Gravity

H - Elevation above Sea Level

h - Layer Thickness of a Geological Unit

L - Latitude

M - Mass of the Earth

R - Radius of the Earth

ρ - Density

ρ_c - Density Contrast Between Granodiorite and Monterey Formation

ρ_R - Density of Crustal Material

ρ_w - Density of Sea Water

SBA - Simple Bouguer Anomaly

TC - Terrain Correction

Z - Distance from Sea Surface to the Ocean Floor

Z_t - Distance from Sea Surface to Mean Sea Level

ACKNOWLEDGEMENTS

The author wishes to express his appreciation for the helpful guidance provided by his advisors, Dr. Robert S. Andrews and Dr. Joseph J. von Schwind of the Naval Postgraduate School (NPS) Department of Oceanography. Dr. Howard Oliver of the U. S. Geological Survey (USGS), Menlo Park, California, loaned the land gravimeter for the shoreline portion of the survey. Dr. S. L. Robbins, also of USGS, provided modifications of the Swick tables for terrain corrections. Mr. Cliff Gray of the Naval Oceanographic Office's gravity section was instrumental in making the underwater gravimeter and auxiliary equipment available. Dr. Rodger Chapman of the California State Division of Mines and Geology provided the most recent Bouguer gravity maps of the Central California area for data analysis. Mr. H. Gary Greene, USGS marine geologist, was most helpful in directing the author's examination of the related geology in southern Monterey Bay. Dr. Warren Thompson, Professor of Oceanography, supplied the necessary ocean tidal records. The author is greatly indebted to Captain Woodrow Reynolds and the crew of the R/V ACANIA for their cheerful and professional help in all aspects of the survey. Mr. Dana Mayberry, the NPS Oceanography Department's electronics technician, assisted the author time and again in the many problems of meter circuitry. Several members of the NPS Public Works Department lended tangible logistic support in many ways, and thanks go to Mr. Pete Wisler,

Mr. Herschel Crosby, and Mr. Jim Levine. Finally, the survey would not have been possible without the assistance of co-workers Lt. Brian Cronyn, USN, and Lcdr. Antonio Souto of the Portuguese Navy.

I. INTRODUCTION

Geological oceanographers have three principal means of investigating structures below the ocean floor: seismic, magnetic, and gravimetric surveys, the latter of which is the subject of this writing. The relatively small variations in the acceleration of gravity over the surface of the earth are largely due to such obvious factors as position, elevation, crustal density, and local terrain; once these effects which may be unrelated to substructure irregularities are removed, however, the investigator is left with a meaningful residual in the form of the complete Bouguer anomaly (CBA). This measure of anomalous attractive force per unit mass then constitutes a basis for the interpretation of the upper few hundreds or thousands of feet of the earth's heterogeneous crust.

This study is based upon measurements made at 10 land stations and 82 underwater stations which were occupied in the spring and summer of 1972. The bottom gravity data collected was obtained aboard the Naval Postgraduate School's (NPS) research vessel R/V ACANIA (Fig. 1).

A. SURVEY PURPOSE

The main purpose for conducting this survey was to learn more about the structural geology of southern Monterey Bay by obtaining gravity data in areas too shallow for larger vessels capable of surface gravimetry. Such vessels must stabilize their course and speed for several minutes after each turn

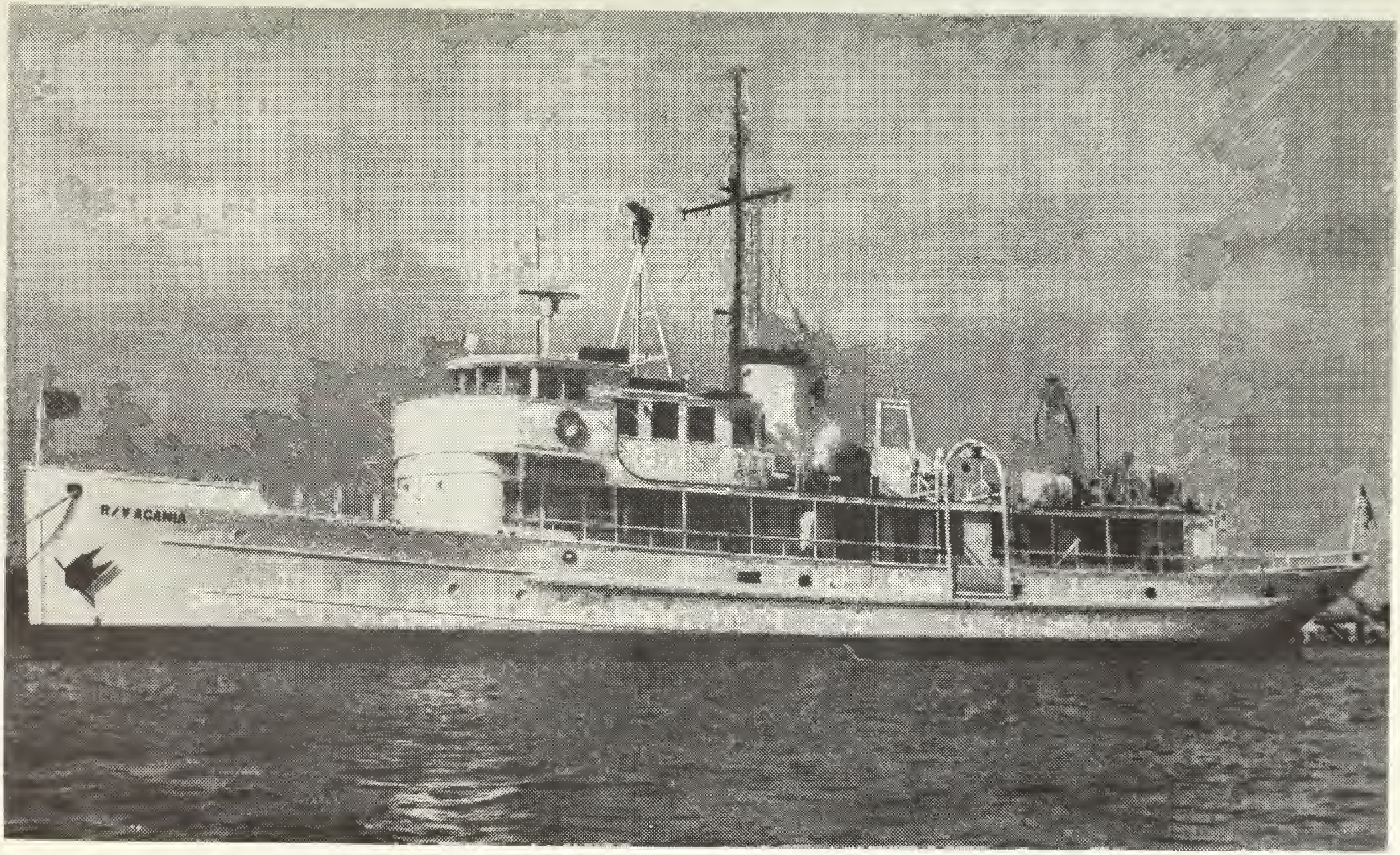


Figure 1. U. S. Naval Postgraduate School's Oceanographic Research Vessel R/V ACANIA.

before useful data can be obtained; this usually places prohibitive restrictions on how close to shore the vessel may work, depending upon local bathymetry. But such geographical restrictions do not apply to bottom gravimetry, since the research vessel can slowly decelerate to even very shallow stations and stop for meter lowering and measurement. The R/V ACANIA was able to survey within 100 yards of the beach in water less than 50 ft deep. Additionally, bottom gravimetry is generally more accurate than sea surface gravimetry due to the stability of the measuring platform, the sea floor. Another advantage of bottom gravimetry is its closer proximity to the density contrasts that produce a gravity anomaly; surface ship measurements must contend with the attenuating effect of vertical distance from the meter to the substructure (Beyer, et al., 1966). This means that the deeper the station, the greater the accuracy of bottom gravimetry over surface gravimetry (assuming equal meter precision).

After a brief area orientation, this report will describe some basic theory of gravity measurements, specific details on equipment used, and various procedures employed during the survey itself. This will be followed by a section explaining each step in the reduction of the raw data, and an analysis of the results in terms of geological significance will conclude the report.

B. AREA DESCRIPTION AND GEOLOGICAL SETTING

Monterey Bay is located about 70 miles south-southeast of San Francisco, California. It is characterized by gently

sloping sandy bottoms in the north and south, divided by one of the largest submarine canyons in the world. The area encompassed by the author's survey includes that portion of southern Monterey Bay within the 50-fm depth contour from Pt. Pinos to Moss Landing (Fig. 2).

With the exception of the rocky bottom in the extreme southwestern portion of the survey area and the predominance of green muds near the Monterey Submarine Canyon, a sandy ocean floor exists in southern Monterey Bay. Cretaceous Santa Lucia granodiorite, readily visible at Pt. Pinos and constituting much of the adjacent sea floor, is buried to increasing depths beneath less dense sediments and sedimentary rocks as one proceeds toward the Salinas River mouth-Moss Landing area (Fig. 3). Much of the overlying material to the north and east is the Monterey Formation, a Miocene rock consisting largely of silicious mudstone, diatomite, and marine shale, interbedded with beds of opaline chert. Above the Monterey Formation are thin layers of the Pliocene Paso-Robles Formation and Pleistocene Aromas red sands. Thinner layers of deltaic deposits from the Salinas River have been laid down above these formations during the Holocene period. Additionally, the Pliocene Purisima Formation, abundant in northern Monterey Bay, has recently been found along the south wall of the Monterey Submarine Canyon (H. G. Greene, personal communication, 1973).

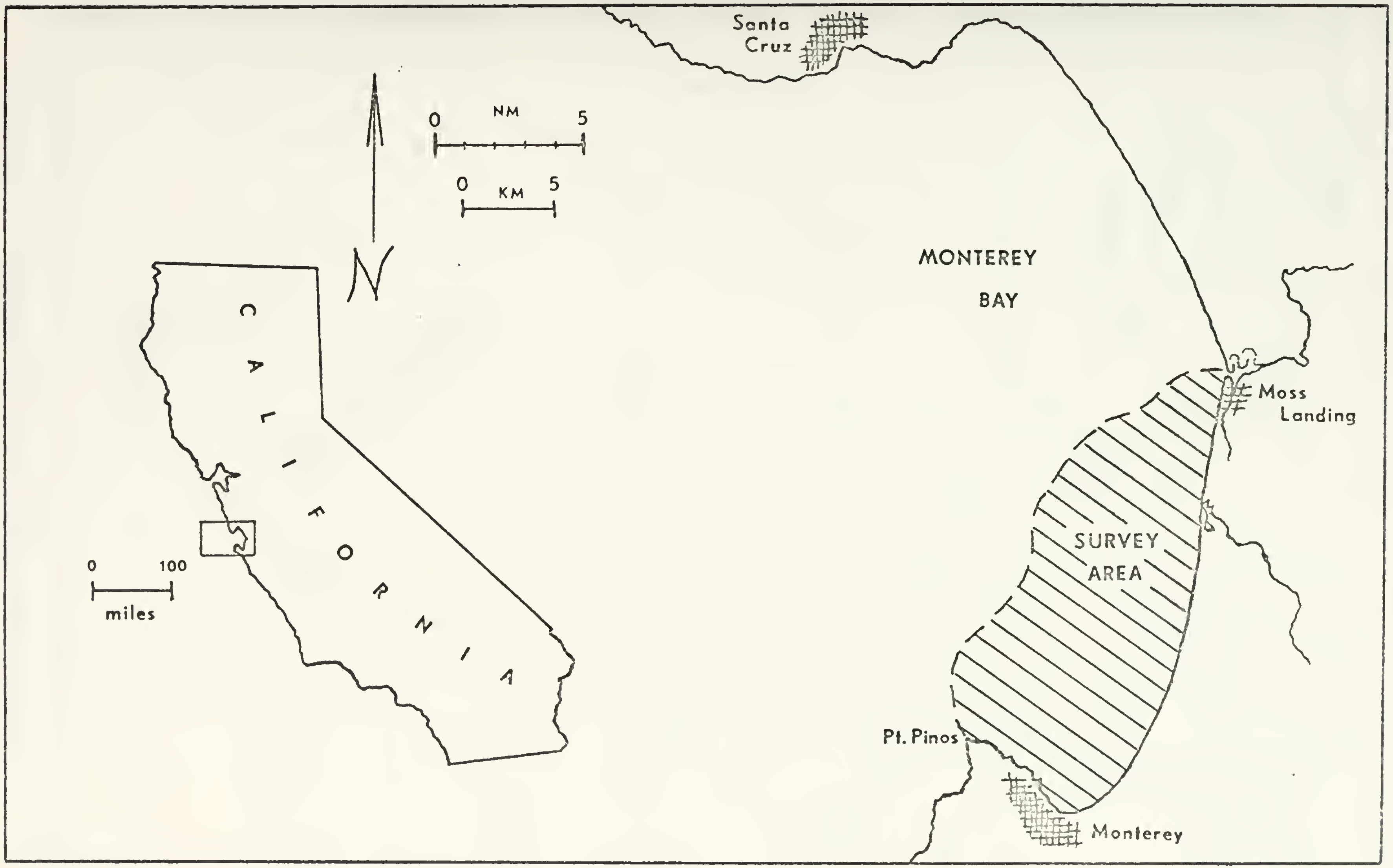


Figure 2. Survey Area.

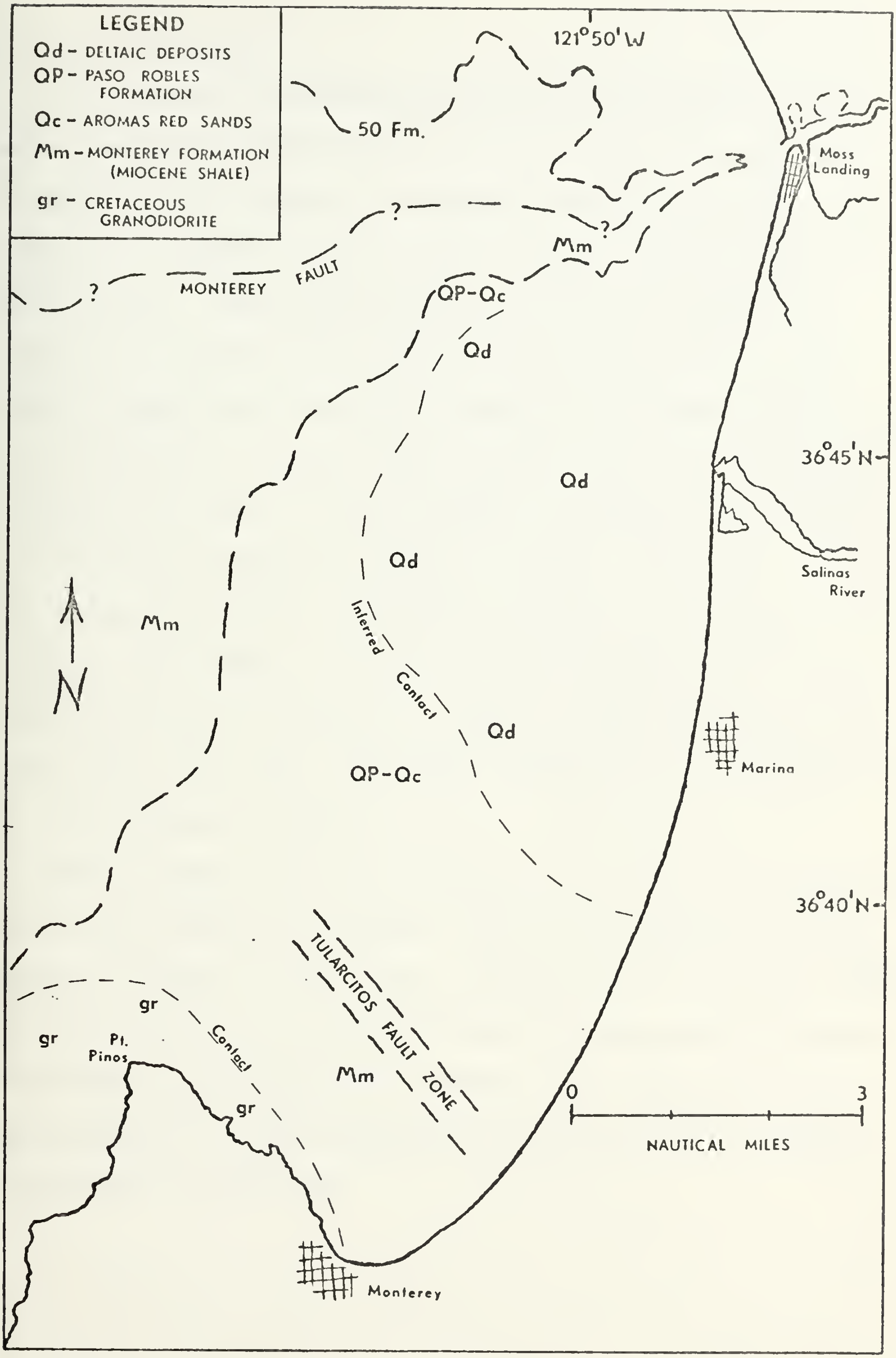


Figure 3. Geological Map of the Survey Area (after Greene, 1970).

C. PREVIOUS WORK

Past geological investigations of Monterey Bay have mainly concerned themselves with the origin and present structure of the Monterey Submarine Canyon, as seen in the studies by Shepard (1948), Martin (1964), and Martin and Emery (1967). Geological research in the shallow water regions of the Bay has been conducted, but most of these efforts investigated specific geological properties, such as bottom sediment type and distribution. The first extensive and detailed report of the geology of southern Monterey Bay was recently presented by Greene (1970). This work reviewed the results of previous bathymetric data, rock dredges, and grab and core samples, as well as the author's own seismic reflection survey results, in order to make inferences concerning the salt water intrusion problem in the aquifers of the lower Salinas Valley.

While gravity data has heretofore been totally absent in the shallow off-shore regions, various investigators have surveyed adjacent land areas. Fairborn (1963), Sieck (1964), and Ivey (1969) have surveyed the local Monterey-Salinas-Ft. Ord region, and Bishop and Chapman (1967) compiled land gravity data from many sources in preparing their Bouguer gravity map of the area.

II. THEORY OF GRAVITY MEASUREMENTS

A. INSTRUMENTS

When the variation of a quantity is extremely small compared to the value of the quantity itself, measurement of that variation requires some method of exaggeration in order to achieve desired sensitivity. Such is the case at hand: gravity values at the equator and the poles are approximately 978 and 983 gal, respectively (owing mainly to the poleward decreases of the local radius of the planet and the centrifugal force due to its rotation); hence, the entire range of possible variation relative to the mean value is about 0.5%. Additionally, this small total range of values is about a hundred times greater than the range observed in Monterey Bay, so the requirement for precise instrumentation is clear. Most of the numerous different gravimeter designs that have become operational over the years illustrate this idea. Depending upon operating principle, they fall under one of two general categories: stable and unstable systems.

1. Stable Gravimeters

Stable gravimeters use a spring-balance system wherein the attractive force on a known mass suspended from the end of a spring is linearly proportional to the resultant elongation. In the case of the Hartley gravimeter, the minute elongation is made more measurable by passing a small, horizontally-hinged beam through the spring-mass system and attaching a

mirror close to the unhinged end, where beam displacement is greatest (Fig. 4). Light from a simple remote source is reflected onto a graduated scale for the observation of relative differences. A micrometer screw attached to an auxiliary spring is located near the hinged end of the beam so that the light beam may be brought back to some fixed reference position. The amount the micrometer screw is turned to accomplish this zeroing process is thus a measure of the difference between the local gravity value and the value associated with the reference position. The system is termed stable because the only force acting to counter gravity is the spring restoring force.

2. Unstable Gravimeters

For deflections of the mass in the unstable (or astatic-balance) gravimeter, the force of gravity is supplemented in increasing the spring elongation's restoring force by a third force which acts in the same sense as that of gravity itself. The Thyssen gravimeter is a typical example (Fig. 5). The clockwise moment of an auxiliary mass above the pivot point results in additional beam displacement which can be kept linearly proportional to gravity. Thus, greater sensitivity is the chief advantage of the unstable gravimeter; for a given change in gravity, the unstable device will undergo greater beam displacement than that of a comparable stable gravimeter.

B. OCEANIC VERSUS LAND GRAVIMETRY

In the case of land gravity meters, systems like those described above are enclosed in an instrument roughly the size

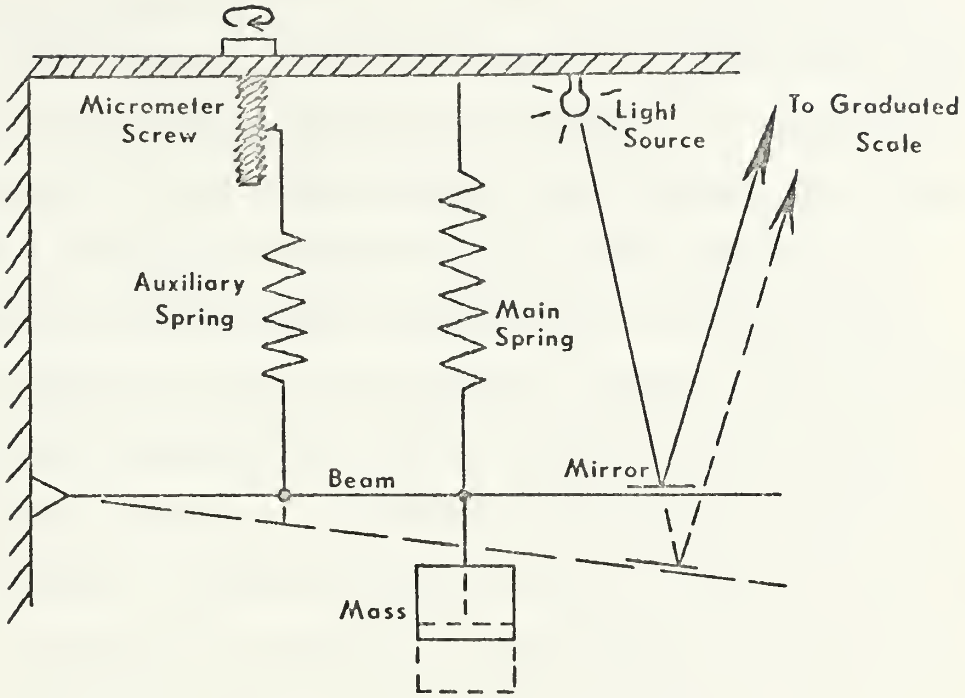


Figure 4. Schematic of a Stable Gravimeter: the Hartley Model (after Dobrin, 1960).

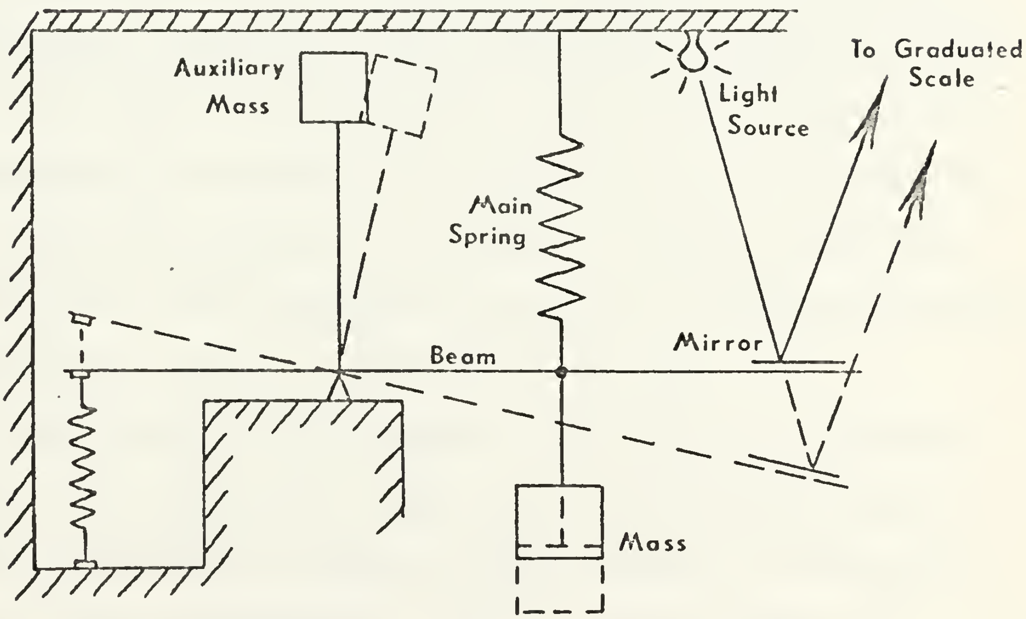


Figure 5. Schematic of an Unstable Gravimeter: the Thyssen Model (after Dobrin, 1960).

of a kitchen toaster, and are therefore as mobile as the operator. The mass is manually clamped in place after each reading and the only electrical requirement is a battery to provide power for the light source, scale illumination, and temperature regulation (necessitated by the temperature-dependence of the expansion coefficients of the springs).

With regard to oceanic gravimetry, however, the situation is vastly more complicated. Three platform options are: surface ship, submarine, and bottom measurements; each has its own drawback. Surface ship gravimetry requires intricate sensors to measure the effects of ship-motion accelerations. Submarines designed for oceanographic research are still quite rare; military submarines have severe space limitations and the more pressing function of national defense to attend to. Bottom gravimetry (conducted with operators accompanying the meter to the bottom in diving bells prior to the 1950's) involves the expensive business of remote control. In addition to these monetary problems, all types of oceanic gravimetry must contend with the formidable problem of accurate navigation, a difficulty not common to most land surveys.

Other difficulties are inherent and peculiar to bottom gravimetry. The gravimeter itself must be enclosed within some type of waterproof chamber strong enough to withstand pressures of many atmospheres. Also, a large number of separate electrical conductors, normally within the insulation and armor of an oceanographic cable, must be employed to effect the numerous recordings and operating modes. This requires a

specialized winch with a multitude of slip-rings. Rocky or steep bottoms can incline the instrument to an extent beyond the range of the leveling gimbals. But perhaps the most challenging problem of all is the requirement that the research vessel maintain its position above the stationary meter, despite drift induced by wind and current. If this requirement is not met, and the winch operator has not lowered sufficient excess cable, the meter may be dragged and jarred while in the unclamped mode, thereby damaging the meter's delicate spring suspension system.

III. EQUIPMENT

A. GRAVIMETERS

Of the two general types of meters discussed in the previous section, the LaCoste and Romberg models fall in the unstable category. Figure 6 is a drawing of the main components. When the mass is released from its protective clamps for the purpose of taking a reading, its motion to an equilibrium position is impeded by very heavy air damping; it therefore takes a finite time interval for the mass, support beam, and light beam to come to rest. The speed of the motion of the light beam is a function of the position of the measuring screw and is indicated by a beam position galvanometer which may be connected to a strip chart recorder. The slope of this record of time versus speed is a measure of how close the measuring screw is to the equilibrium position, which, in turn, is a measure of gravity.

The zero-length spring in Figure 6 was first introduced by LaCoste in 1934 for use in an innovative long period vertical seismograph. Its unique method of manufacture renders elongations or compressions proportional to increases or decreases in gravity itself, resulting in increased sensitivity.

The calibration of most other types of gravimeters depends on weak auxiliary springs which are connected directly to the measuring screws (Figs. 4 and 5). This is avoided in LaCoste and Romberg gravimeters by employment of a lever system connected to the measuring screw. The light beam is thereby

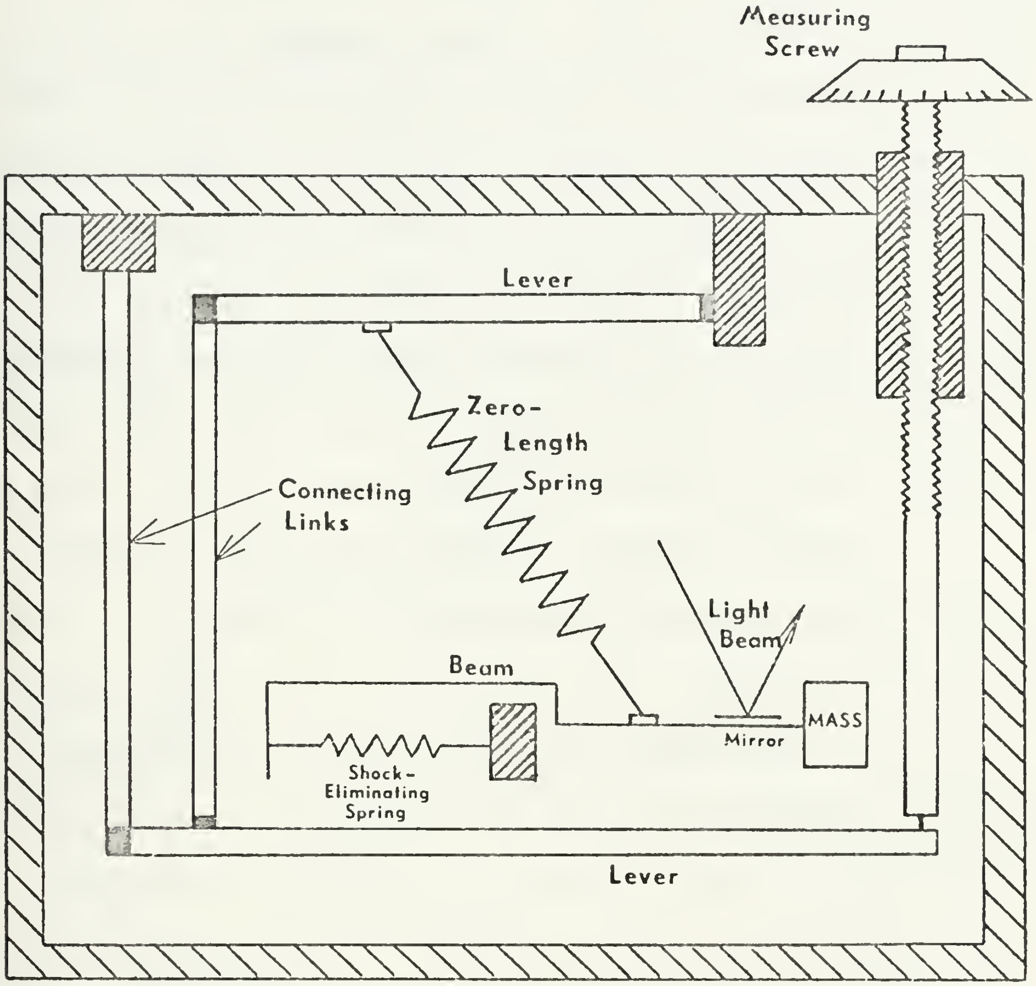


Figure 6. Simplified Diagram of the LaCoste and Romberg Gravimeter (after LaCoste, 1967).

brought to the equilibrium position by actually changing the location of the zero-length spring's upper support.

1. <u>LaCoste and Romberg Model G-17B Geodetic Land Gravimeter</u>

The LaCoste and Romberg model G-17B geodetic land gravimeter used for the shoreline survey is an instrument housing the system just described in a 5-3/4 inch x 6-1/2 inch x 8-1/2 inch case weighing about 5 lb. This model was first introduced in 1956, and operates in the field on battery power over a 7000 mgal range. Instrument drift is less than 0.5 mgal/month due to a thermistor-transistor heater control system. Sealed against atmospheric pressure changes, the G-17B gravimeter is nulled by adjusting the measuring screw while observing the light beam positon through a microscope eyepiece.

2. <u>LaCoste and Romberg Model H6G Underwater Gravimeter</u>

The LaCoste and Romberg Model H6G underwater gravimeter used for the bottom survey is a complete system which permits an instrument like the G-17B to be used on the ocean floor. Simply stated, it is a remote-controlled land gravimeter inside a shell of two thick aluminum hemispheres supported by a triangular base (Fig. 7 and 8). A brief description of the features of this model is presented in Table I.

B. AUXILIARY EQUIPMENT

The bottom gravimeter and all of the associated equipment were loaned to the NPS Oceanography Department by the U. S. Naval Oceanographic Office in Suitland, Md. Engineered and assembled by the Geophysical Equipment Manufacturing Co. of Houston, Tex., the auxiliary equipment's operation may be

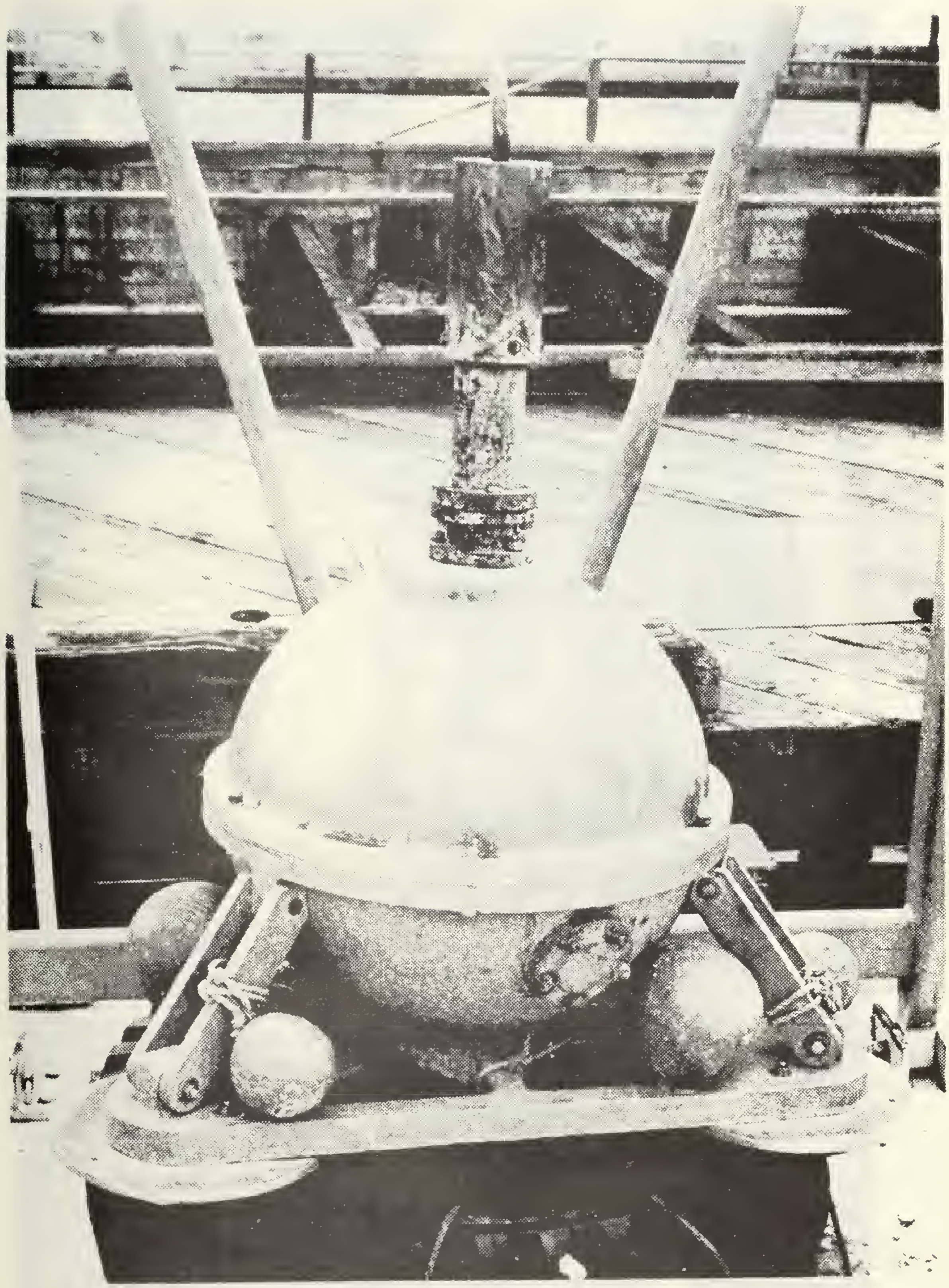


Figure 7. Model H6G Gravimeter Ready for Use.

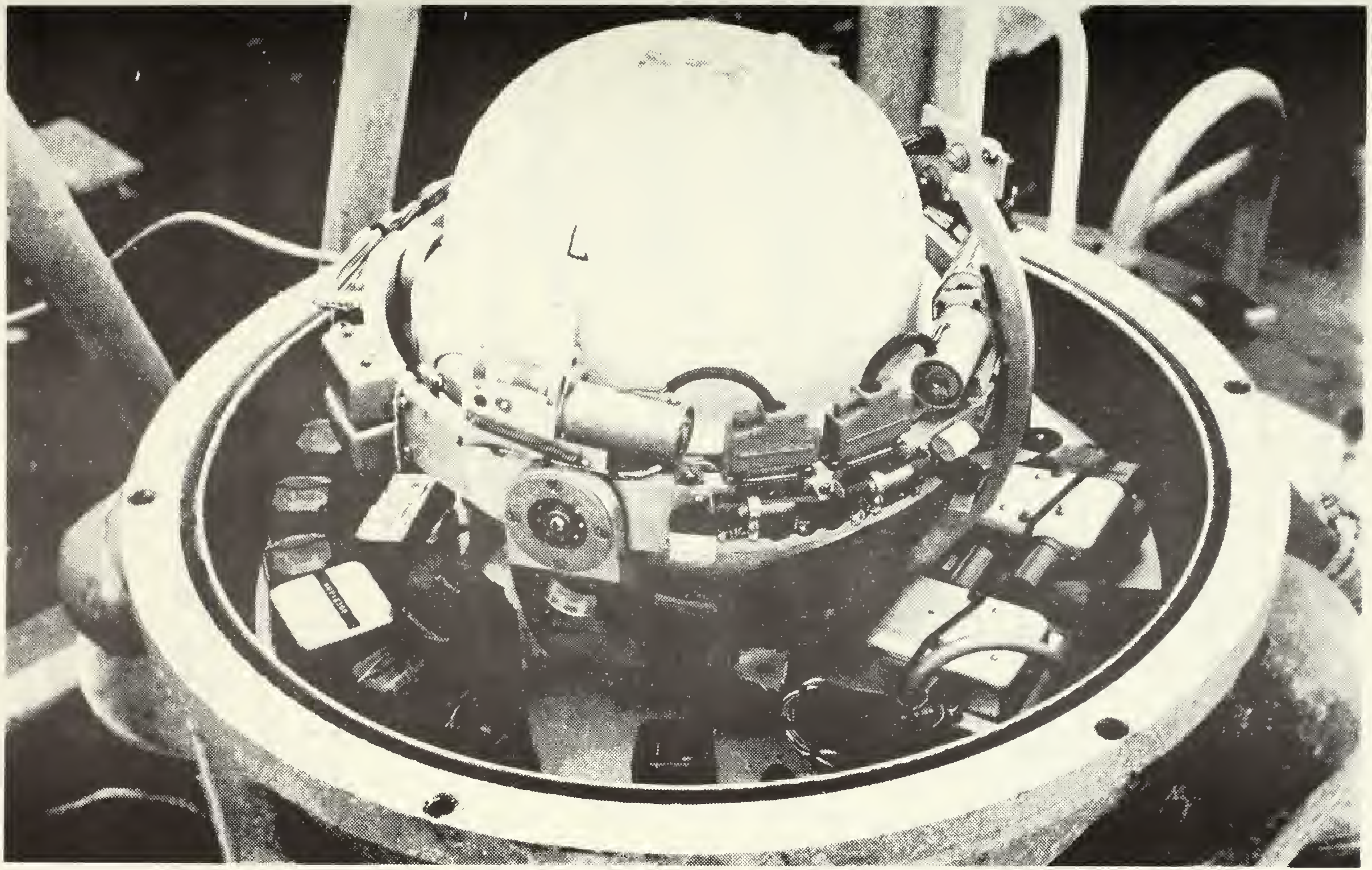


Figure 8. Internal View of the Model I6G Gravimeter.

Table I. Features of the LaCoste and Romberg Model H6G Underwater Gravimeter

Base Size (with legs)	39-inch equilateral triangle
Height	29 inches
Weight	350 lb, including enough weight to insure acceptable sink rate
Range	World wide (7000 mgal)
Optimum Accuracy	$\pm$0.02 mgal
Realistic Accuracy	$\pm$0.10 mgal
Power Source	115 vac, 60 Hz
Routine Maximum Operating Depth	600 ft
Maximum Operating Depth Tested	2900 ft
Maximum Bottom Slope Permissible	15°
Depth Indication	Pressure sensor (0.5% accuracy) connected to casing port
Leveling System	Optically-controlled servo motors driving rack and pinion assemblies
Flood Indication	Open circuit, 1/4-inch gap, inside bottom of lower hemisphere

summarized as follows: a gasoline engine provides mechanical energy to a hydraulic pump transforming the rotary motion into hydraulic pressure (Fig. 9). This hydraulic pressure is used to operate both the winch and A-frame using two, two-way control valves. One valve controls a hydraulic motor which converts the fluid pressure back into rotary motion to drive a heavy-duty chain link connected to the winch reel's shaft. The A-frame is hinged at deck level and actuated from above by two hydraulic pistons controlled by the other valve.

With the gravimeter connected electrically to the termination at one end of the cable, the other end is routed inside the hollow shaft of the winch and out the side to a slip-ring assembly. The outer side of the slip-ring assembly is wired to a cannon plug connection on the control box, which in turn is connected through a rectifier and an isolation transformer to one of the ship's 115 vac outlets, the basic power source for the entire electrical system.

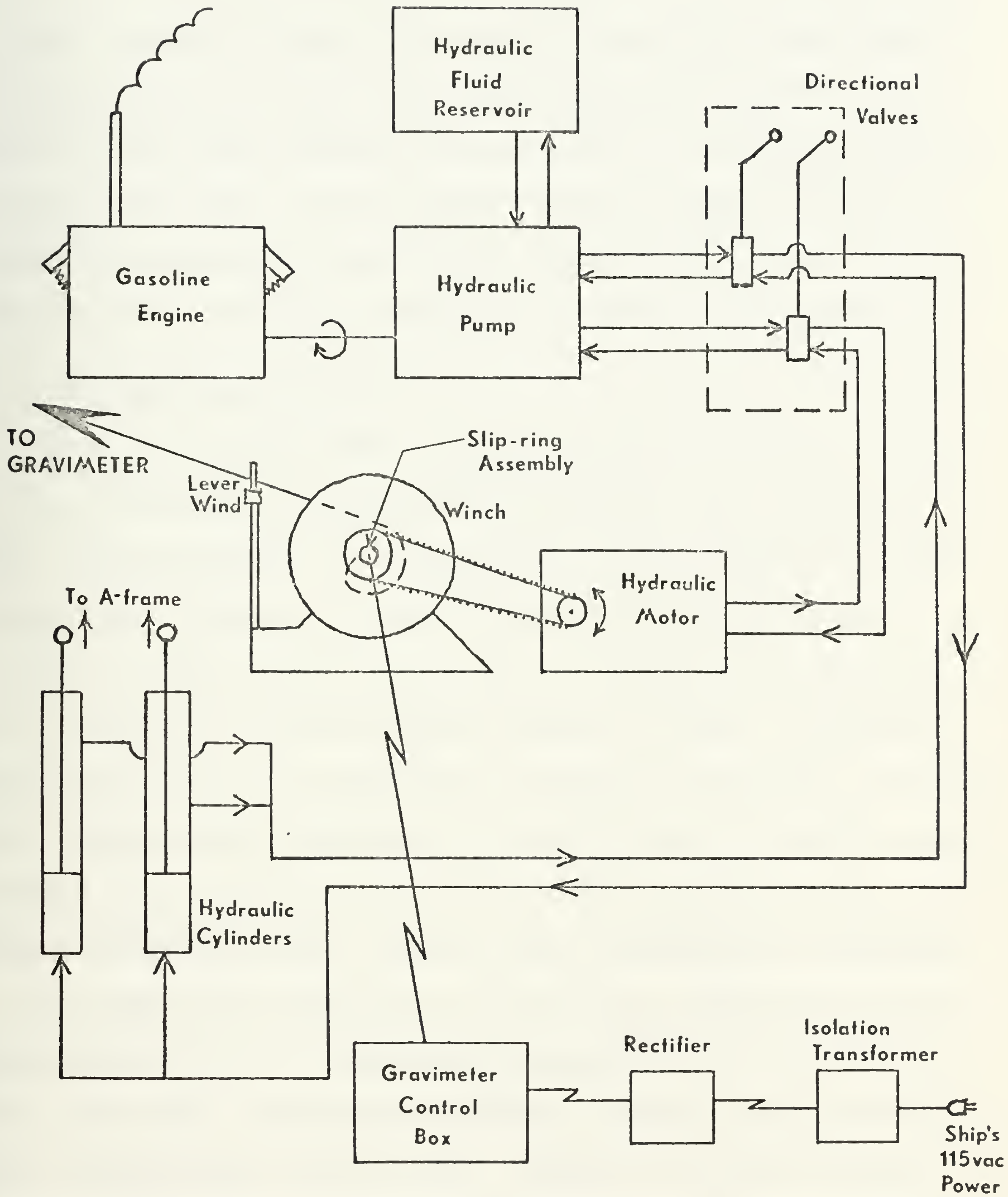


Figure 9. Schematic Diagram of the Auxiliary Equipment.

IV. PROCEDURE

This survey was part of a larger effort to investigate off-shore gravity values over a more extensive area: two co-workers (also NPS students) recorded data in northern Monterey Bay and Carmel Bay. Since bottom gravity studies are by no means a one-man operation, they were assisted by the author and provided similar assistance to him during his survey.

A. GRAVIMETER CALIBRATION

Prior to beginning the shoreline survey on 26 April 1972, the land meter was calibrated by the author and co-workers under supervision of U. S. Geological Survey (USGS) personnel. Readings were taken at several benchmarks from USGS headquarters in Menlo Park (USGS 1 JD) to Skeggs Point Scenic View (U. S. Coast and Geodetic Survey Station B-388), a frequently used calibration route spanning a range of 137.20 mgal (Chapman, 1966). Subsequent reduction of counter values to gravity values resulted in a difference of 137.15 mgal over the entire range. Smaller differences were found at the intermediate benchmarks.

The underwater gravimeter was initially calibrated by the manufacturer prior to shipment to Monterey in the spring of 1972. After the survey was completed, another calibration check of the meter was in order. Early in 1973 the author occupied CA-259 (Woollard Airport Base WA-84) at the Monterey County Airport and a benchmark located at the base of the steel tower on the Monterey Coast Guard pier, designated WH-29 by

Woollard and Rose (1963). The meter readings resulted in a gravity difference less than 0.5 mgal greater than the 22.5 mgal established value (Chapman, 1966). The difference was probably due to the recent construction of a second terminal building next to CA-259. Since the airport value is lower than the pier value, and since the effect of the new building is an additional upward attraction, the difference between the two reference stations has probably increased due to the new construction. In view of this consideration, as well as the fact that the published location of the CA-259 benchmark could not be found exactly (due to the construction), it is estimated that the observed gravity difference between the airport and pier stations was within 0.1 mgal of the true value.

B. SHORELINE SURVEY

A preliminary gravity survey of the perimeter of southern Monterey Bay was undertaken in late April, 1972, with the land gravimeter discussed above. The information from this shoreline survey of 10 stations was later used to verify the nearby CBA values and isoline trends of the underwater survey, since land gravimetry is an order of magnitude more accurate than oceanic gravimetry. (While land gravimeters are read to the nearest 0.01 mgal and subsequent corrections' accuracies can lead to CBA values of 0.1 mgal accuracy, remote-controlled bottom gravimeters, read to the nearest 0.1 mgal, can result in a CBA accuracy of at best 1 mgal.) In addition to verifying the bottom survey results, these land stations also served to

tie in the combined survey with previously surveyed areas inland. All 10 land stations were located (vertically) within a few feet of sea level so that the small magnitude of the subsequent gravity corrections would yield better CBA accuracies. The stations were fairly evenly spaced from Pt. Joe to Moss Landing (Fig. 10). Visual estimates of station level relative to the average existing sea surface elevation were recorded at each station, so that station elevations relative to mean sea level could be calculated later from tidal information. Exact locations and depths/elevations of both underwater and shoreline stations are included in Appendix A.

C. SHIPBOARD INSTALLATION AND SEA TRIALS

When the auxiliary equipment arrived in Monterey in late June, 1972, preliminary inspection indicated that it had been some time since the system was used. A re-termination of the cable and an engine overhaul were required before the survey could begin.

An initial concern was the question of location of the equipment aboard the ship. It was decided that the after section of the upper level would be most suitable in view of the physical requirements associated with meter lowering and the intended length of stay of the equipment aboard. The A-frame, supporting plate, and gravimeter were stationed on the starboard side so that the data recorder in the dry lab directly below would be able to observe cable speed and direction of motion (Fig. 11). Also, the crane's location in close proximity

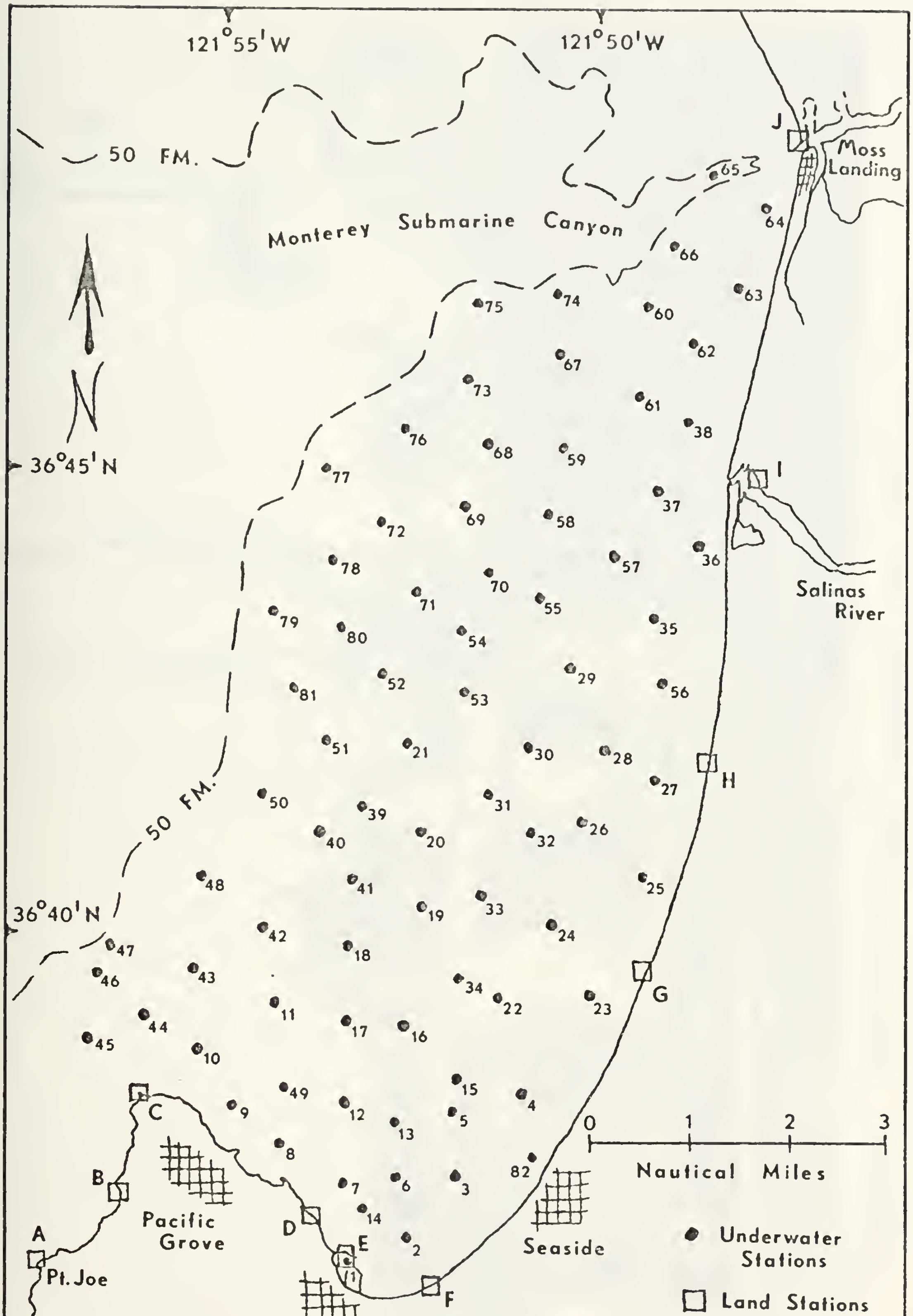


Figure 10. Station Locations.

Figure 11. Auxiliary Equipment Installed Aboard the R/V ACANIA.

on the starboard side seemed compatible with the plan to bring the meter to and from the main deck for each station. The winch was placed abeam the A-frame area but on the port side, in an attempt to spread out the 4 ton weight of the equipment. The engine and hydraulics stand were located on the ship's centerline and slightly forward of the other components.

A brief sea trial period was arranged prior to the start of the actual survey in order to acquire a familiarity with conditions to be encountered. A trial station was occupied west of Seaside, California, in about 100 ft of water. SCUBA divers accompanied the meter to the bottom to observe the sink rate, take some underwater photographs, and determine if excessive cable would foul the feet of the gravimeter. However, a strong wind and too little excess cable resulted in dragging the meter across the sandy bottom while the meter was in the unclamped mode. It was decided to return to the ACANIA's mooring to check for possible damage to the mass suspension system. Fortunately the counter reading reproduced the value obtained just prior to departure for the station, a sign that no damage had been sustained.

This preliminary venture into the Bay showed that the stations would have to be occupied with the ship's bow into the wind so that the major wind-induced position corrections could be accomplished with ahead or astern engine commands. Since the ACANIA has no bow-thruster, the bow could be kept into the wind with alternate use of one or both of the engines and rudder. Also, a feel for the amount of cable payed out as

a function of cable angle and tension was obtained, since the divers reported that cable fouling about the base of the meter was a remote possibility (owing mainly to the cable's large diameter and resultant large radius of curvature).

D. SURVEY OPERATIONS

Prior to the onset of the survey, selection of station locations was governed mainly by the requirement for a fairly evenly-spaced grid from which an accurate scalar field of the CBA could be extracted. In view of the size of the survey area and the expected ACANIA availability periods, it was felt that a minimum of 75 stations would be needed to satisfy this requirement. A chart showing the spacing of about 100 intended stations similar to Figure 10 was provided to the bridge for course information. Whether the actual stations occupied coincided with these intended positions was not of great concern; the important thing was to determine the position of each station as accurately as possible during and immediately after its occupation in order to adjust the planned location of the next station for a possible gap in coverage. Stations were numbered in order of occupation (except for those on land). Upon completion of the survey, the 92 stations occupied covered an area of 50 sq n mile, representing a station density of almost 2 per sq n mile (Fig. 10).

1. Navigation

With the exception of three stations occupied during morning fog (and consequently requiring radar positioning),

all of the bottom station positions were determined by visual lines of bearing from prominent landmarks during hours of both daylight and darkness. Three or four such bearings were taken at each station, and these were often supplemented by radar distances from coastline features. Standard navigational procedures were used to estimate the true location of the ship's position in the small area where lines and arcs of position converged. Most of the three-line position triangles were on the order of 0.1 n mile or less on a side, and a good portion of the plots were point fixes. Bearing-taking was begun as soon as the ACANIA became dead-in-the-water (before the meter was lowered to the bottom) and was always completed well before the meter was raised after the measurement. When it appeared the vessel was drifting, a second set of bearings was taken. Differences in meter position and ship's position at each station were thus small enough to safely neglect consideration. In view of these factors, it is stated with a high degree of reliability that station position errors at sea were at worst 0.1 n mile. If such an error was in a north-south direction the value of theoretical gravity and final CBA would differ by only 0.14 mgal.

Land station navigation was less complex and far more accurate. Six of the ten stations were selected for occupation because their exact location was clearly shown on the charts used. While the other four station locations were transferred to the chart from hand drawn maps, it is certain that their position accuracy was at least twice as good as that of the oceanic stations.

2. Measurements

During the survey the meter was first lowered to the sea surface and a depth counter value was obtained by nulling the appropriate galvanometer; this was repeated as soon as the meter reached the sea floor. Next the leveling mode was selected and required flood and tilt checks were made. (Only at 2 of the 82 bottom stations did the greater-than-15° bottom slope indication appear, requiring repositioning of the meter.) After the high-speed leveling switch was activated to make coarse leveling adjustments, the meter was put into the read mode. In this mode, while fine leveling adjustments continued automatically, the beam position and gravity counter switches were alternately used to stop the motion of the beam position galvanometer needle in the null position. During this process the correct counter value was always approached from the same direction (namely, from too low a counter value) to avoid hysteresis errors. When what was determined to be the correct counter value was obtained, an over-adjustment of 0.1 counter units was introduced to check for a reversal in the direction of beam position motion. This method of obtaining the gravity counter value is not only much faster than the slope method used with the strip chart record of time versus beam speed, but also about as reliable (H. B. Parks, LaCoste & Romberg, Inc., personal communication, 1972). After the gravity counter value was recorded the mass was again clamped in the deck mode and the meter raised.

The meter was normally on the bottom for about 4 or 5 min, 2 or 3 min of which were spent in the read mode. Including transit time between stations (but excluding transit time to and from the first and last stations of each track), the 82 bottom stations were occupied in a total of 25 hours, yielding an average rate of better than 3 stations per hour, or about 18 min per station. The deepest stations usually required the most time.

At the shoreline stations the land gravimeter was leveled visually with two bubble glasses and manually operated screws attached to the frame. The scale was then illuminated with a light switch and the mass was manually unclamped. Correct counter values were obtained by simultaneously observing the beam position through the microscope eyepiece and manually adjusting the measuring screw to null it in the reference position.

Fortunately, snycronization between the counter readings of the bottom gravimeter and the control box was maintained throughout the author's survey. Between the August and September cruises, however, loss of snycronization did occur once. This was evident when a routine counter reading at Station 1 was several milligals from its standard value, and the loss required opening the inner gravimeter case to read its counter value so that the control box counter value could be reset to agree.

An important set of measurements midway through the survey, accomplished by repetitive occupation, established a

3.20 mgal difference between Station 1 on the floor of Monterey Harbor and Station E, the USCG pier benchmark. In addition to tieing in all bottom gravity readings with a reference benchmark value, this result also related values recorded by the two different meters with a station common to both surveys.

3. Environmental Effects

From a climatological viewpoint, the summer months are best suited, due to wind conditions, to gravity operations in southern Monterey Bay. By observing surface bubble relative motion as well as cable angle, the ship's master was usually able to maneuver the R/V ACANIA to avoid being blown downwind of the desired position directly above the meter. The wind-induced sea and swell presented more of a problem to survey operations by causing noticeable pitch and roll. This occasionally resulted in the gravimeter hitting the extended A-frame during lowering and raising evolutions.

Readings taken in shallow depths were often characterized by a slowly fluctuating beam position in addition to the normal motion of the beam position prior to obtaining the final reading. This required observation of the rate of change of the position of the fluctuation's mean so that the gravity counter switch could be used to eventually hold this mean in a fixed position. Since the automatic averaging capability of the control box was inoperative, the averaging process had to be done by eye, thereby introducing an estimated reading error of 0.1 counter units into the final counter values.

The fluctuating beam position was, in part, the visual indication of a form of micro-seismic bottom motion caused by surface swell and wave activity, its influence on beam position being a function of depth and type of bottom sediment (LaCoste, 1967). Additionally, a swaying of the cable was probably felt by the meter through the rigidly-attached cable termination. The effect of this problem on survey operations was the need for more time in the read mode to obtain the correct counter value, and, hence, the occupation of fewer stations per hour.

Fog conditions often prevail in the east central region of Monterey Bay during the early morning hours of spring and summer. Such was the case during the occupation of Stations 36, 37, and 38. Its only effect upon the survey was a slight deterioration of positioning accuracy; in the absence of visual contact with distant landmarks, radar navigation was utilized.

V. DATA REDUCTION AND PRESENTATION

The method whereby the raw data collected during the survey is transformed into a meaningful CBA picture is discussed below. Although much of the theory involved in data reduction applies to both land and ocean stations, there are important differences. Some of the individual corrections discussed apply only to bottom gravity data; a summary of the reduction methods applicable to land stations follows in a separate section.

The majority of the required calculations were accomplished through use of the NPS IBM-360 computer. Programs were written by the author in Fortran language and numerical significance was double precision. Copies of these programs are included at the end of this report.

A. OBSERVED GRAVITY

As pointed out earlier, gravimeters measure gravity differences rather than absolute gravity values. Since gravity counter units as recorded from the gravimeter control box are numerically close to, but not exactly equivalent to, milligals, they must first be converted to milligals before addition to or subtraction from a reference gravity value. The absolute reference used for this survey was 979891.7 mgal, the gravity value at WH-29 on the Monterey Coast Guard pier. In practice a more convenient intermediate reference station at the mooring buoys (Station 1) was used to tie in all of the other station readings and to monitor meter drift.

The control box counter reading at the pier benchmark was 3323.05 units; hence, the formula used for computing observed gravity at each bottom station was:

$$g_o = 979891.7 + \left[(CV_o - 3323.05) \times (1.03985) \right] \qquad (1)$$

where g_o is in milligals and CV_o represents the observed gravity counter value at the station in question. The 1.03985 factor converting counter unit differences to milligals was obtained from a table provided by the manufacturer listing (a) a milligal value associated with each even hundred counter units as well as (b) conversion factors for values between the counter units listed. Since all of the stations' observed counter values fell between 3300 and 3400, only one such conversion factor from the listing was required.

B. LATITUDE CORRECTION

The first correction (although the order of various corrections is not defined in any mandatory way) applied to the observed value of gravity is normally the subtraction of the theoretical value of gravity based on geographical position. The determination of theoretical gravity obviously requires a precise knowledge of the shape of the earth so that the distance from the surface to the earth's center and the centrifugal force are known for any location. The actual geometry has been determined to be very nearly a triaxial spheroid, or ellipsoid of revolution having depressions along the two 45° latitude lines and a flattening and bulging of the equator (Dobrin, 1960). Years of geodetic investigation have yielded numerous revised coefficients for the equation of this

reference spheriod to more accurately approximate the earth geoid. The author's selection of a particular equation was governed (as were all aspects of data reduction) by a desire to conform with the procedures of USGS and the California State Division of Mines and Geology in an effort to render the final CBA map compatible with existing land gravity maps. The coefficients used were those of the 1930 International Spheroid, the theoretical value of gravity being a function of latitude only (Dobrin, 1960):

$$g_t = 978049.0\ (1 + 0.0052884 \sin^2 L - 0.0000059 \sin^2 2L) \quad (2)$$

where L is the latitude. Equation (2) results in a predicted south-to-north increase in the value of local theoretical gravity of 1.44 mgal/n mile.

The assumption that the geoid and the reference spheroid coincide would appear erroneous at first glance, since, in fact, they can differ vertically by as much as 50 m in some regions of the world. However, a more meaningful measure of the validity of the effect of this assumption is the change in this difference over the area of interest. In the small domain of Monterey Bay, the change in the distance from the equipotential surface of the geoid to that of the reference spheroid is on the order of a few centimeters. It may therefore be concluded that final CBA values will still result in an accurate representation of small-to-intermediate scale geological features of the upper crust (Grant and West, 1965).

C. EARTH TIDE CORRECTION

In that the interior of the earth possesses finite elasticity, the attractive forces of heavenly bodies (particularly the moon and sun) continually act to deform its shape. As is the case with the ocean surface, the pertinent manifestation of this phenomenon is a small scale vertical fluctuation of the earth's crust which can affect observed gravity values to a measurable extent. The true distance from a point on the surface to the earth's center can change by as much as 1 ft in a matter of hours, representing a 0.1 mgal change in gravity; thus, the effect of these earth tides on gravity measurements made over such an interval of time must be considered.

The USGS earth tide Fortran program was utilized to obtain the required corrections. Dates and times of station occupation along with a geographically-central location of 36° 42' N, 121° 52' W were the input parameters. The output values were tabulated at 20 min intervals. A copy of this program may be obtained from the NPS Department of Oceanography, Code 58Ad.

D. DRIFT CORRECTION

Readings taken at Station 1 before and after each track were, more often than not, slightly different. These differences were attributable to three causes:

(a) earth tidal variation during the time interval between base station occupations;

(b) ocean tidal variation during the same period;

(c) meter drift.

Since the ACANIA was secured to fixed mooring buoys in an east-west orientation, possible north-south variation in the actual location of Station 1 before and after each track was negligible. To determine true meter drift it is only necessary to remove the effects of (a) and (b) above from the total "apparent drift" actually measured. Recalling that counter unit differences are very nearly equivalent to milligal differences, earth tide variation was removed directly from counter readings. Similarly, the changes in attraction due to different sea surface tidal heights above the meter were removed. (Each 1 ft of water above the meter decreased observed gravity by 0.0127 mgal.) The resultant drift values for each track were then applied linearly over the range of stations. The greatest drift rate was 0.036 mgal/hour.

E. FREE-AIR CORRECTION

The formula for the value of the Newtonian portion of gravity (in milligals) for a unit mass at sea level (g_n) is:

$$g_n = \frac{G\ M}{R^2} \tag{3}$$

where G is the universal gravitational constant ($6.670 \times 10^{-5} cm^3 g^{-1} sec^{-2}$), M is the mass of the earth, and R is the distance to the earth's center. The free-air correction (FAC) to gravity data accounts for the fact that the measurement was made at some elevation other than mean sea level, the assumed height of the surface of the reference spheroid. (A gravity station located exactly at mean sea level, then, would not require this correction.) Disregarding the mass between

the station and sea level for the time being, the free-air correction is obtained by differentiation of (3) (Heiskanen and Vening Meinesz, 1958):

$$FAC = \frac{dg_n}{dz} \times (H) = (0.09406 \text{ mgal/ft}) \times (H) \qquad (4)$$

where H is the elevation of the station above mean sea level. A simple modification of this equation yields a formula which applies to bottom gravimetry:

$$FAC = (0.09406 \text{ mgal/ft}) \times (\text{Water depth} - \text{Tide height}) \qquad (5)$$

Since equation (3) implies decreasing values with increasing distance from the center of the earth, the free-air correction is negative for underwater stations.

A first-order gravity anomaly, the free-air anamoly (FAA), is obtained with the inclusion of this correction along with others mentioned thus far:

$$FAA = g_o - g_t \pm ET \pm D - FAC \qquad (6)$$

where g_o, g_t, and FAC are as defined by equations (1), (2), and (5), respectively, ET being the earth tide correction, and D the drift correction.

The free-air correction effectively refers station level to sea level, and is easily the largest single correction to be applied. It is therefore clear from equation (5) that accurate values of station depth and tide level are critically important if an acceptable degree of precision is to be achieved. The pressure sensor in the gravimeter chamber provides depth counter indications from the sea surface to the sea bottom; the difference in the surface and bottom readings

is converted to depth in feet by means of a linear relation extracted from sensor calibration graphs provided by LaCoste and Romberg.

All tide heights used were based on the assumption that the existing tide level at each station in the survey area was identical with that simultaneously recorded in Monterey Harbor. Levels were recorded by the NPS tide recording device located in the assistant harbormaster's office on Municipal Wharf No. 2 in Monterey Harbor. A reference line was drawn on these records at 5.5 ft above staff zero. Mean sea level is 5.9 ft above Monterey's staff zero (H. V. Maixner, personal communication, 1973). Thus, tide height distances were measured relative to 0.4 ft above the reference line. These tide values were compared with appropriate values from the published 1972 tide prediction tables (U. S. Department of Commerce, 1972); agreement was very good. In order to make this comparison it was necessary to determine the vertical distance from mean lower low water to mean sea level for Monterey, since all tide table values are referenced to mean lower low water. This difference was found to be 2.7 ft.

F. BOUGUER CORRECTION

While the free-air correction is concerned with changes in the denominator of the right-hand side of equation (3), the Bouguer correction (BC) addresses changes in the numerator. This correction considers how the attraction between the mass within the gravimeter and the earth's center of mass is

affected by (a) the presence of material between the station's elevation (or depth) and sea level, and (b) the density of this material.

The method of the Bouguer correction first assumes that the measurement was made on an infinitely flat ocean bottom, so local terrain irregularities are temporarily neglected. Removing the upward attraction of an infinite slab of overlying water whose thickness equals the station depth would effectively replace that slab of water with air and result in a higher value of observed gravity. Since the formula for the attraction of such an infinite slab is $2\pi G \rho h$, where ρ is the density and h is the thickness (Dobrin, 1960), the first part of the Bouguer correction (BC_1), the removal of the sea water's attraction, is:

$$BC_1 = 2\pi G \rho_w Z \tag{7}$$

where Z is the pressure sensor depth and ρ_w is the density of sea water. The second part of the Bouguer correction (BC_2) accounts for the increased downward attraction for the sea water that would have existed had the measurement been made at mean sea level (thus, the previous inclusion of the free-air correction is assumed):

$$BC_2 = 2\pi G \rho_w (Z-Z_t) \tag{8}$$

where Z_t is the tide height relative to mean sea level. The third and final part of the Bouguer correction (BC_3) considers the additional downward attraction that would have existed had the material between sea level and the ocean bottom been an infinite slab of crustal material instead of water:

$$BC_3 = 2\pi G\ (\rho_R - \rho_W)\ (Z-Z_t) \qquad (9)$$

where ρ_R is the density of average crustal material. Figure 12 summarizes these considerations schematically. The total Bouguer correction is then:

$$BC = 2\pi G \rho_W Z + 2\pi G \rho_W (Z-Z_t) + 2\pi G\ (\rho_R - \rho_W)(Z-Z_t) \qquad (10)$$

or, combining terms,

$$BC = BC_1 + BC_2 + BC_3 = 2\pi G \rho_W Z + 2\pi G \rho_R (Z-Z_t). \qquad (11)$$

The density of sea water was taken as 1.027 g/cm^3, and an average crustal density of 2.670 g/cm^3 was used for ρ_R. It is clear from Figure 12 that the Bouguer correction is positive for underwater stations. Once it is included with the other corrections, the simple Bouguer anomaly (SBA) emerges:

$$SBA = g_o - g_t \pm ET \pm D - FAC + BC \qquad (12)$$

Or, from equation (6),

$$SBA = FAA + BC. \qquad (13)$$

Just as bottom gravity data is reduced to the complete Bouguer anomaly in order to compare it with land gravity anomalies, its reduction to a gravity anomaly intermediate between the free-air and simple Bouguer anomalies will permit comparison with FAA values as determined by a surface ship. By only adding BC_1 and BC_2 to the free-air anomaly of the bottom data, such a value is obtained (Fig. 12-4 applies). This may be referred to as a "mass-adjusted" free-air anomaly (FAA').

Since the free-air and Bouguer corrections are both functions of station depth, pressure sensor errors must be examined to determine their effect on these corrections. A 1-ft depth error produces a combined FAC/BC error of 0.05 mgal

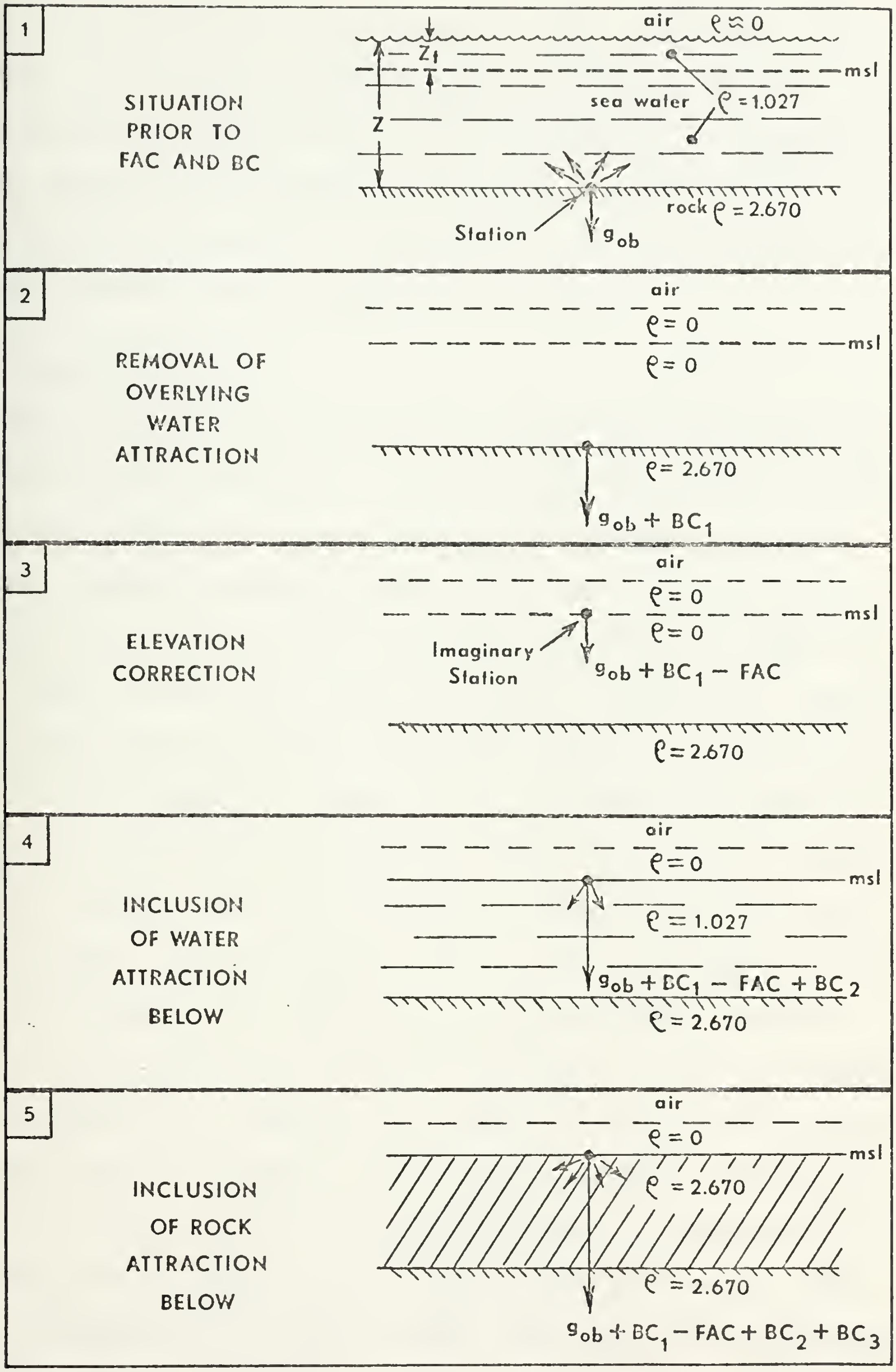


Figure 12. Schematic Representation of the Free-Air and Bouguer Corrections. (All densities are in g/cm^3.)

(the two corrections are of opposite sign). Although the manufacturer's claim of pressure sensor accuracy is 0.5% (this would correspond to $\pm$ 2.3 ft for the deepest station), a more conservative assessment was used. It was assumed that the depth determination was in error by 4 ft at most, so the combined FAC/BC error is $\pm$ 0.20 mgal or less.

G. TERRAIN CORRECTION

Easily the most time-consuming aspect of gravity data reduction is the topographic, or terrain correction (TC). Oftentimes this correction may be ignored altogether (J. D. Rietman, personal communication, 1972), and this has been generally true for previous underwater gravity work (much of which seems to have been done in the Gulf of Mexico). However, due to the close proximity to Monterey Bay of very deep abyssal plains in the Pacific, as well as such intermediate-scale features as the Monterey Submarine Canyon and various coastal mountain ranges, this sort of simplification would be unrealistic at best. (In the final result, quite noticeable differences were found in the positions of SBA and CBA isolines spaced at an interval of 5 mgal.) Consider a gravity station on the ocean floor located on the upper rim of a deep trench. The fact that the trench is filled with sea water produces a smaller value of observed gravity than would be measured if the trench were filled in with solid crustal material. The upward attraction of a nearby guyot would also act to decrease observed gravity. Thus any terrain deviation above or below station level reduces observed gravity relative to its flat-

bottom value, both on land and under the sea surface. This correction is therefore always positive.

The generally accepted method for calculating the gravitational attraction of topographic irregularities was first developed by Hayford and Bowie in 1912. It consists of approximating the volume of excess or deficit terrain surrounding the station with a series of concentric cylindrical shells of varying height (depending on the local elevation or depth). In plan view this appears as a set of circular zones; the zones are lettered alphabetically from the station outward and divided into many compartments. This bulls-eye representation is then put on glass or acetate templates scaled to conform with appropriate topographic or bathymetric charts. By centering such a template on the station, the average elevation or depth of each compartment is estimated to determine its distance above or below station level. This difference between compartment and station level is the entering argument for tables which have been developed to give the corresponding gravitational attraction in milligals. The compartment corrections (199 in all) are then summed to yield the total terrain correction.

The tables used in this research are modifications by the USGS of the work done by Swick in 1942. His tables are based, in turn, on Bullard's 1936 modification of the original Hayford-Bowie paper that presented the combined effects of topography and isostatic compensation. These tables assume a removal/fill-in density of 2.670 g/cm^3, and give a 0.615 multiplication

factor for the corrections in oceanic compartments. (Since not air but sea water of density 1.027 g/cm^3 fills oceanic compartments to sea level, only 1.643 g/cm^3 additional mass density, or 61.5% of 2.670 g/cm^3, is needed to complete the terrain correction density fill-in.) As one would expect, the tables' corrections decrease for a given elevation difference with increasing distance from the station, and increase for a given zone with increasing elevation differences. Thus the elevation difference effectively adjusts the value of the numerator of equation (3), while the zone specification does the same to the denominator.

The effect of terrain upon a gravity value measured on the sea floor is more complex than its terrestrial counterpart; this is understandable in view of the inclusion of an additional medium, the sea water, surrounding the station. This effect must be computed in three stages; Figure 13 presents the analysis in cross-section.

Had the sea floor (Fig. 13-A) been horizontal, a terrain correction would not be required. The existence of a uniform slab of 1.027 g/cm^3 material extending infinitely in all directions between station level and sea level can be neglected without changing the TC value to be calculated since the topographic effect of such a slab of given density and of constant thickness equals zero. The first step shown in Figure 13 simplifies the problem and requires no actual calculations; it effectively replaces the sea water in Sector 1 with air and decreases the crustal density in Sector 4 to 1.643 g/cm^3. The

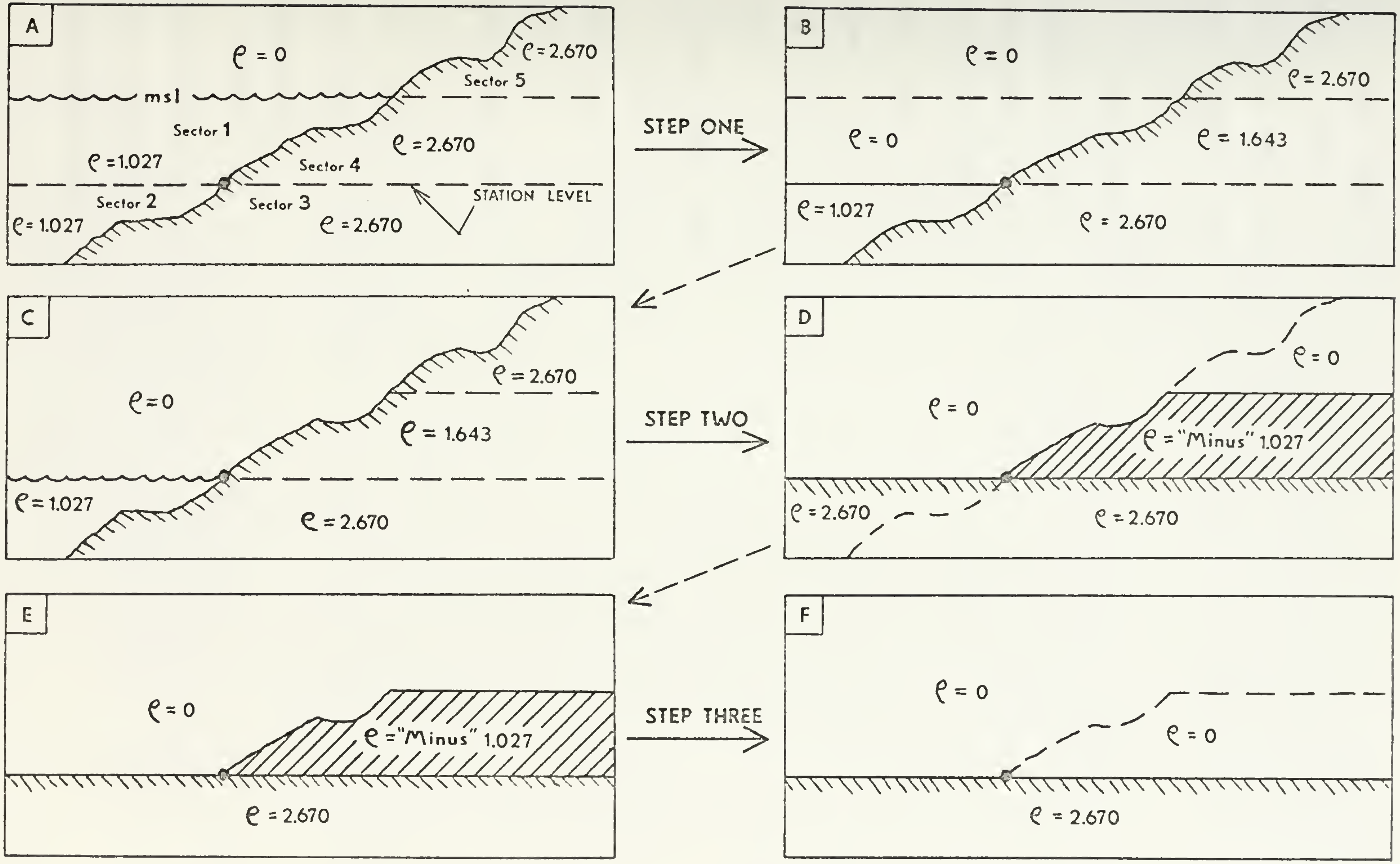


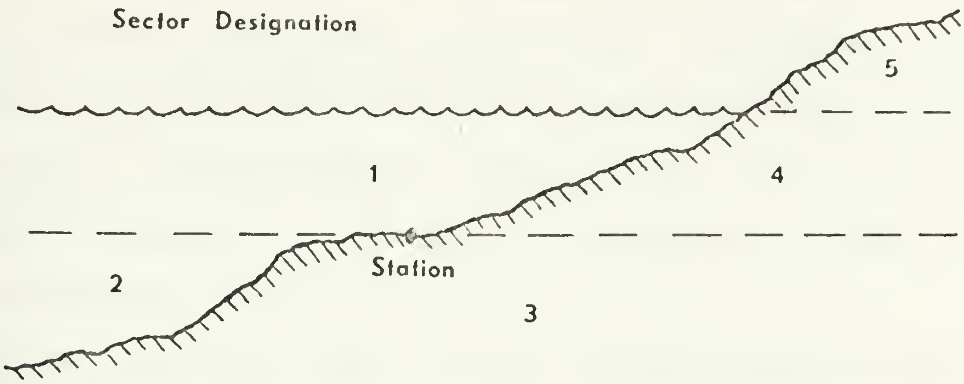
Figure 13. Schematic Representation of the Terrain Correction for a Gravity Station on the Sea Floor. (All densities are in g/cm^3.)

resultant mass distribution surrounding the station shown in Figure 13-B has an attractional effect (due to terrain) identical to that shown in Figure 13-C, i.e., as if the station had been located right at the coastline of a layered continent of two different densities.

Step two consists of a "normal" terrain correction as described earlier. Land compartment corrections are sub-totaled and added to 61.5% of the sub-total of the corrections for oceanic compartments. This step effectively transforms the sea water in Sector 2 into rock of density 2.670 g/cm^3, and removes rock of similar density from Sectors 4 and 5. Sector 5 is now air (as desired), but the use of a density of 2.670 g/cm^3 was excessive in Sector 4, since its density was only 1.643 g/cm^3 after step 1 (Fig. 13-D).

Step three corrects this situation by "putting back" material of density 1.027 g/cm^3, thereby making Sector 4 a region of air. This last step is accomplished by subtracting from the previously accumulated total correction after step 2 a correction based on only one elevation (station depth) for all landward compartments. It is 38.5% (the density ratio of sea water to crustal rock) of the subtotal thus obtained from the tables.

Adding the total terrain corrections to the data refers the resulting gravity anomalies to their values had the station been located on a flat earth crust (Fig. 13-F). Table II summarizes the steps just described.



	Step One	Step Two	Step Three
Sector 1	Decrease sea water density to zero.	No Change	No Change.
Sector 2	No Change.	Increase water density to that of rock.	No Change
Sector 3	No Change.	No Change.	No Change.
Sector 4	Decrease rock density by an amount equal to sea water density.	Decrease density present by 2.670 g/cm^3.	Increase present density by 1.027 g/cm^3 to yield zero effective density.
Sector 5	No Change	Decrease rock density to zero.	No Change.

Table II. Summary of Terrain Correction Procedure for a Gravity Station on the Sea Floor. (Steps one and three are unique to bottom gravimetry.)

It would not be possible after step 1 to compute separate corrections for Sectors 4 and 5 with density ratio factors of 0.615 and 1.0, respectively. This is due to the fact that the tables were developed with the assumption that the base of each land compartment is at station level.

Most of the maps, charts, and templates required were provided by USGS. One such template was constructed by the author, however, scaled for use with U. S. Coast and Geodetic Survey (USC&GS) Chart No. 5403. The bathymetric information on this chart was considerably better than that of others available, and was especially helpful for corrections in Zones E through I.

It should be kept in mind that the slope of the bottom in Figure 13 is greatly exaggerated. Since bottom slopes in most of southern Monterey Bay are on the order of 1:100, many stations' cumulative corrections as far out as Zone G totaled zero. For this same reason the considerations of steps 1 and 3 were, in practice, not required. Sector 4 compartment elevations could never exceed station depth and were always negligibly smaller within the closest several zones, with the exception of Station 65 (located on the eastern end of the thalweg of the Monterey Submarine Canyon). Here, a simple multiplication by the 0.615 density ratio factor sufficed for the Sector 4 corrections. As this number is usually used to transform water in Sector 2 into rock, it similarly transforms rock in Sector 4 into water. This simplification was possible because Sector 5 corrections for Station 65 are nill (since

the elevations of the area surrounding Moss Landing are so small). The fact that the Sierra Nevadas are just beyond the 100-mile radius of the most distant zone (Zone 0) and that the San Juaquin Valley is so uniformly flat and close to sea level also served to expedite calculations somewhat.

A realistic assumption regarding possible errors in estimating compartment elevations is $\pm$ 0.02 mgal per zone. If errors of this magnitude and similar sign existed in each of the 15 zones, the total terrain correction error would be $\pm$ 0.30 mgal for each station.

The foregoing analysis treats the terrain correction independently of the earlier Bouguer correction. This is valid since the Bouguer correction assumes a flat station environment (Heiskanen and Vening Meinesz, 1958). Independent analysis is further justified by considering a change in the order of making the corrections: applying a pure terrain correction to the free-air anomaly, followed by the Bouguer correction, should result in an identical CBA. Regardless of order, the free-air correction only looks at vertical distance, the Bouguer correction deals with vertical mass attractions, and the terrain correction accounts for quasi-horizontal mass attractions.

H. CURVATURE CORRECTION

The curvature correction (CC) may be thought of as a terrain correction of macroscale proportions since it accounts for the curvature of the earth. (Recall that the assumed

ouguer slab was infinitely flat.) For shallow bottom stations, nis correction is negative and is given by equation (14) S. L. Robbins, personal communication, 1972):

$$CC = 4.462 \times 10^{-4} H - 3.282 \times 10^{-8} H^2 + 1.270 \times 10^{-15} H^3 \quad (14)$$

nere CC is in milligals and H is height in feet above sea evel. (Oceanic depths are entered as negative numbers.)

When the terrain and curvature corrections are applied to ne simple Bouguer anomaly, the result is the complete ouguer anomaly (CBA). Its value may be stated in equation orm:

$$CBA = g_o - g_t \pm ET \pm D - FAC + BC + TC - CC \quad (15)$$

r, from equation (12):

$$CBA = SBA + TC - CC \quad . (16)$$

ne CBA is the difference between observed gravity and the alue expected had the station been located on a flat solid urface at sea level, unaffected by astronomical attractions. nis final gravity anomaly refines the geological implications E the SBA and represents a useful tool that geologists can all upon to infer substructure mass distribution.

. SHORELINE SURVEY

Data reduction for the ten stations ashore proceeded in a ashion similar to that of the bottom survey, but with five xceptions. First, since calibration factors for the conersion of counter units to milligals are unique to each articular gravimeter, the equation for g_o for the Model G-17B ravimeter was not the same as equation (1). Second, free-air

corrections were added (rather than subtracted), since on land, mean sea level in general is closer to the earth's center than station elevation. Third, Bouguer corrections were subtracted (rather than added), because part of the observed attraction was due to the material between station level and sea level. Thus, while underwater Bouguer corrections are composed of three parts, terrestrial Bouguer corrections need compensate for only a single attraction. Fourth, the three-step terrain correction analysis does not apply. Finally, since all elevations were within 10 ft of mean sea level, curvature corrections were not required. (A station elevation of 22 ft above or below sea level is required to produce a curvature correction of 0.01 mgal.) The equation summarizing land station data reduction is then:

$$CBA = g_o - g_t \pm ET \pm D + FAC - BC + TC \qquad (17)$$

Estimated error values for land station corrections are $\pm$ 0.02 mgal for g_o, $\pm$ 0.07 mgal for g_t (corresponding to positioning accurate to within 1/20 n mile), $\pm$ 0.06 mgal/ft for station elevation, and, again, $\pm$ 0.30 mgal for the terrain correction elevation estimations.

J. DATA PRESENTATION

The values of the "mass-adjusted" free-air anomaly and complete Bouguer anomaly for both shoreline and bottom stations were recorded on charts next to appropriate station locations and scalar analyses were performed by hand with isolines spaced at a 5-mgal interval (Fig. 14 and 15). Table III presents the values of these and two other gravity anomalies

of interest for the 92 stations; values of observed and theoretical gravity as well as values of the various corrections are presented in Appendix A.

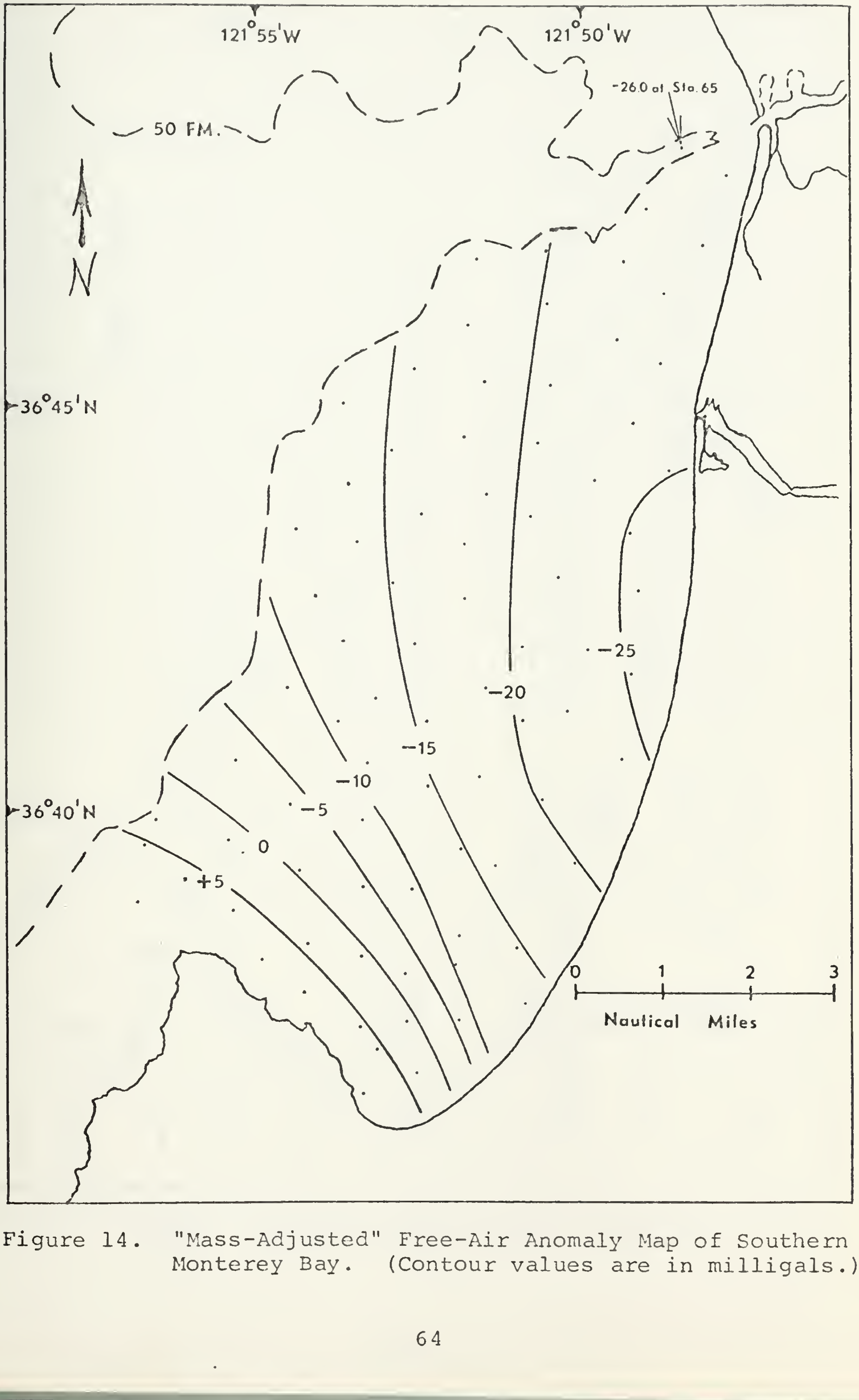


Figure 14. "Mass-Adjusted" Free-Air Anomaly Map of Southern Monterey Bay. (Contour values are in milligals.)

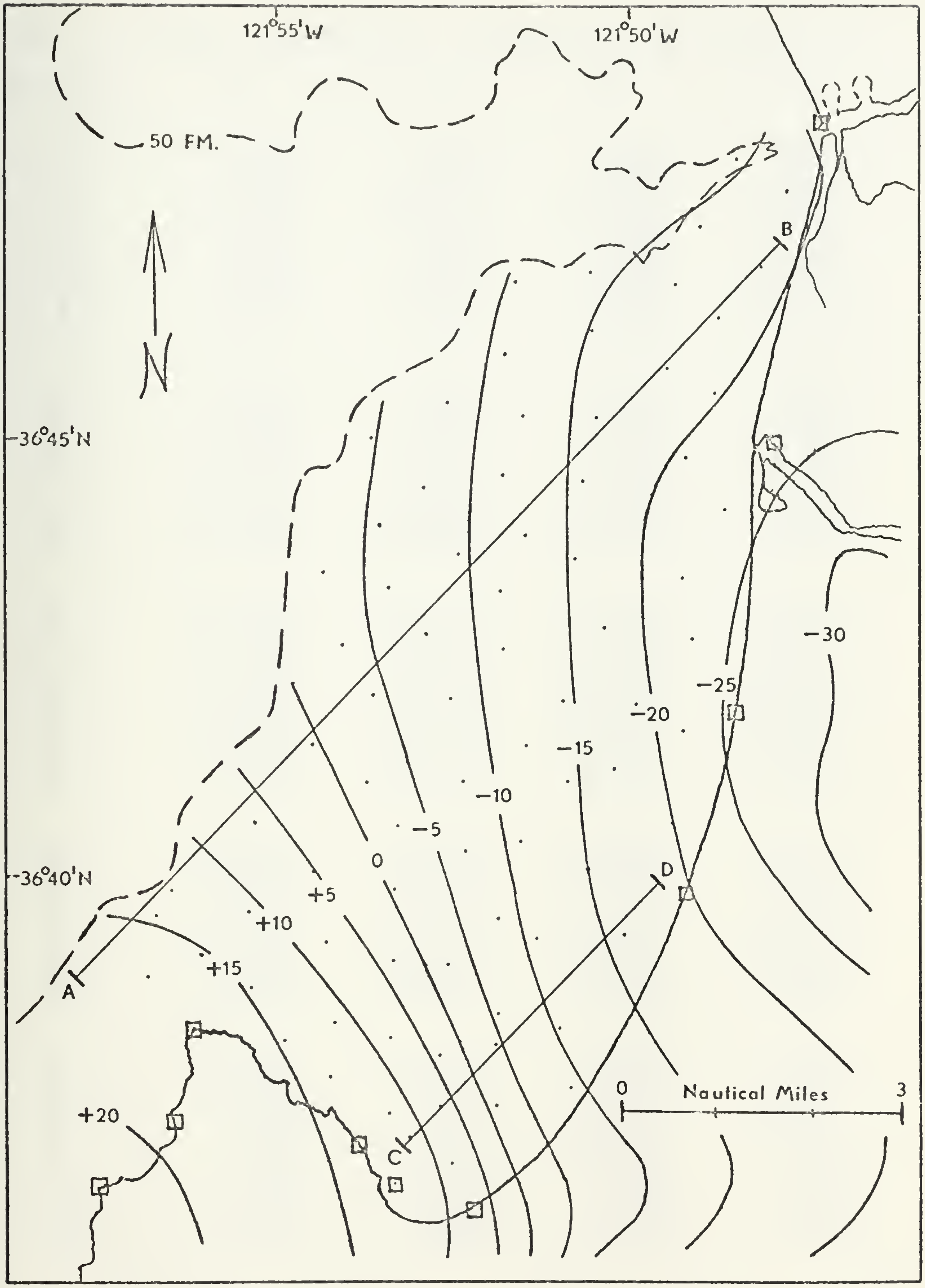


Figure 15. Complete Bouguer Anomaly Map of Southern Monterey Bay. (Contour values are in milligals.)

TABLE III. DATA PRESENTATION. (VALUES ARE IN MILLIGALS.)

STATION	FAA	FAA'	SBA	CBA
1	8.078	9.139	9.997	12.959
2	1.783	3.761	5.349	8.135
3	-7.902	-5.444	-3.474	-0.825
4	-16.926	-14.714	-12.941	-10.399
5	-14.256	-10.267	-7.075	-4.492
6	-3.314	0.309	3.206	5.916
7	2.473	5.996	8.808	11.648
8	6.075	8.157	9.815	12.780
9	6.966	8.947	10.521	13.607
10	5.273	8.681	11.395	14.566
11	-6.959	-0.241	5.120	7.934
12	-4.313	1.253	5.690	8.454
13	-6.932	-1.971	1.981	4.656
14	3.093	5.920	8.163	11.015
15	-16.282	-11.975	-8.550	-6.003
16	-12.734	-7.146	-2.697	-0.103
17	-10.975	-4.576	0.520	3.200
18	-15.408	-8.755	-3.457	-0.792
19	-21.103	-14.961	-10.070	-7.596
20	-22.216	-15.729	-10.561	-8.143
21	-22.131	-15.530	-10.269	-7.903
22	-20.362	-16.258	-12.977	-10.495
23	-21.733	-19.727	-18.126	-15.720
24	-24.094	-20.366	-17.388	-15.071
25	-25.615	-23.745	-22.254	-19.985
26	-25.758	-21.958	-18.924	-16.698
27	-27.460	-25.419	-23.793	-21.697
28	-26.808	-23.369	-20.625	-18.544
29	-26.698	-23.023	-20.089	-18.001
30	-25.718	-20.716	-16.721	-14.506
31	-24.362	-18.562	-13.928	-11.678
32	-25.118	-20.234	-16.332	-14.076
33	-23.154	-17.785	-13.495	-11.126
34	-19.543	-14.460	-10.397	-7.913
35	-27.030	-25.268	-23.856	-21.936
36	-25.863	-24.833	-24.005	-22.122
37	-24.659	-23.225	-22.074	-20.188
38	-23.634	-22.509	-21.606	-19.774
39	-19.796	-12.862	-7.313	-4.862
40	-18.477	-11.256	-5.477	-2.851
41	-18.260	-11.495	-6.082	-3.488
42	-10.885	-3.632	2.169	4.984
43	-5.340	1.793	7.497	10.643
44	1.478	7.556	12.417	15.832
45	3.318	8.685	12.976	16.615
46	-1.939	5.143	10.804	14.302
47	-5.887	2.036	8.368	11.821
48	-10.363	-2.669	3.478	6.625
49	-1.697	3.828	8.239	11.104
50	-16.089	-8.366	-2.194	0.633

STATION	FAA	FAA'	SBA	CBA
51	-18.504	-11.198	-5.361	-2.797
52	-21.887	-15.103	-9.683	-7.371
53	-23.793	-17.805	-13.021	-10.753
54	-23.833	-18.145	-13.600	-11.448
55	-25.221	-21.157	-17.911	-15.831
56	-27.646	-25.666	-24.088	-22.082
57	-25.620	-23.612	-22.011	-20.026
58	-25.037	-21.165	-18.076	-16.042
59	-24.413	-21.136	-18.524	-16.550
60	-24.643	-21.073	-18.227	-16.348
61	-23.344	-21.460	-19.963	-18.106
62	-23.120	-21.828	-20.805	-18.997
63	-22.447	-21.598	-20.932	-19.177
64	-22.858	-21.905	-21.157	-19.394
65	-38.000	-26.040	-16.491	-13.723
66	-25.055	-21.527	-18.727	-16.597
67	-24.388	-20.401	-17.234	-15.213
68	-24.047	-18.606	-14.278	-12.171
69	-23.559	-17.831	-13.274	-11.173
70	-24.638	-19.562	-15.527	-13.365
71	-23.324	-17.013	-11.992	-9.751
72	-21.888	-15.065	-9.635	-7.374
73	-24.339	-18.043	-13.035	-10.854
74	-24.689	-19.860	-16.025	-13.838
75	-25.312	-18.422	-12.939	-10.558
76	-22.713	-15.664	-10.053	-7.775
77	-21.156	-13.459	-7.329	-4.872
78	-21.485	-14.178	-8.360	-5.968
79	-19.065	-11.201	-4.936	-2.312
80	-21.757	-14.503	-8.726	-6.312
81	-21.836	-14.255	-8.213	-5.554
82	-14.101	-12.753	-11.694	-9.088
A	18.111		18.002	21.842
B	15.358		15.338	19.148
C	12.838		12.835	16.615
D	10.890		10.610	13.820
E	9.344		9.087	12.407
F	4.975		4.937	7.777
G	-23.471		-23.645	-21.145
H	-27.662		-27.740	-25.620
I	-25.079		-25.113	-23.023
J	-23.138		-23.373	-21.403

VI. DATA ANALYSIS AND GEOLOGICAL INTERPRETATION

Figure 15 is in general overall agreement with the regional trend of CBA values on adjacent land areas as determined by Fairborn (1963), Sieck (1964), Bishop and Chapman (1967), and Ivey (1969). The shape of the +10 and +15 mgal isolines is in excellent accord with the shape of the granitic contact north and east of Pt. Pinos (Fig. 3). Additionally, there is a discernible gradient increase from the +10 to -5 mgal isolines in the southernmost region of the Bay; this coincides with the Tularcitos Fault Zone. The previously assumed existence of -30 mgal isolines seaward of the Marina area (Chapman and Bishop, 1967) was due to insufficient station coverage along the coast and no offshore coverage; the -25 mgal isoline in Figure 15 is confirmed by a CBA value of -25.620 at Station H. Monterey Peninsula CBA values were found to be slightly higher than those presented on the 1967 Santa Cruz Sheet, but, again, bottom gravimetry CBA values were verified by the independent land survey (Stations A, B, C, and D). Of far greater geological significance than the actual CBA value associated with each isoline is the general shape and trend of these lines, an aspect of Figure 15 that all investigators concerned could easily accept.

Possible error magnitudes are summarized in Table IV. These estimates are considered to be maximum values; it is felt that the final CBA values of the author's survey are accurate to within 1 mgal.

Table IV. CBA Error Magnitude Estimate. Error values are in milligals.

Data Reduction Step	Error Source	Bottom Survey Error	Shoreline Survey Error
g_o	Meter Accuracy Reading Accuracy	$\pm$ 0.10 $\pm$ 0.10	$\pm$ 0.02 $\pm$ 0.01
g_t	Navigation	$\pm$ 0.14 ($\pm$ 1/10 n mile)	$\pm$ 0.07 ($\pm$ 1/20 n mile)
FAC BC	Depth/Elevation	$\pm$ 0.20 ($\pm$ 4 ft)	$\pm$ 0.12 ($\pm$ 2 ft)
TC	Subjectivity in Compartment Elevation Estimation	$\pm$ 0.30	$\pm$ 0.30
Maximum Estimated CBA Errors:		$\pm$ 0.84	$\pm$ 0.52

It is readily apparent from Figure 15 that the northeastern portion of the survey area is characterized by a deficiency of mass density relative to the southwestern region. This deficiency represents an increase in depth to the top of the dense granitic basement from southwest to northeast, and is in very good agreement with seismic reflection profiles presented by Greene in 1970 (Fig. 16 and 17). Since a single geophysical method seldom assures a unique solution, this confirmation of previous seismic reflection interpretation is an important result of the author's study. The CBA profiles in the figures lack the detail (particularly in the Tularcitos Fault Zone) of the corresponding seismic profiles; this is most probably due to the grid size of the station network. Additionally, there may exist an insufficient density contrast, although this possibility is remote in view of the apparent displacement and the density difference between the Monterey Formation and granodiorite below Monterey Bay.

Figures 16 and 17 indicate an average complete Bouguer gravity anomaly decrease of 5 mgal for each 520 ft increase in depth to the granitic basement structure. Since the 11 n mile extent of profile A-B and corresponding 3700 ft drop in the level of the basement represent a slope at the interface between the Monterey Formation and the granodiorite of only about 3°, we can approximate the difference in attractive forces at two points along that profile whose CBA values differ by 5 mgal by the attraction of a horizontally infinite slab 520 ft thick whose mass density is equal to the density

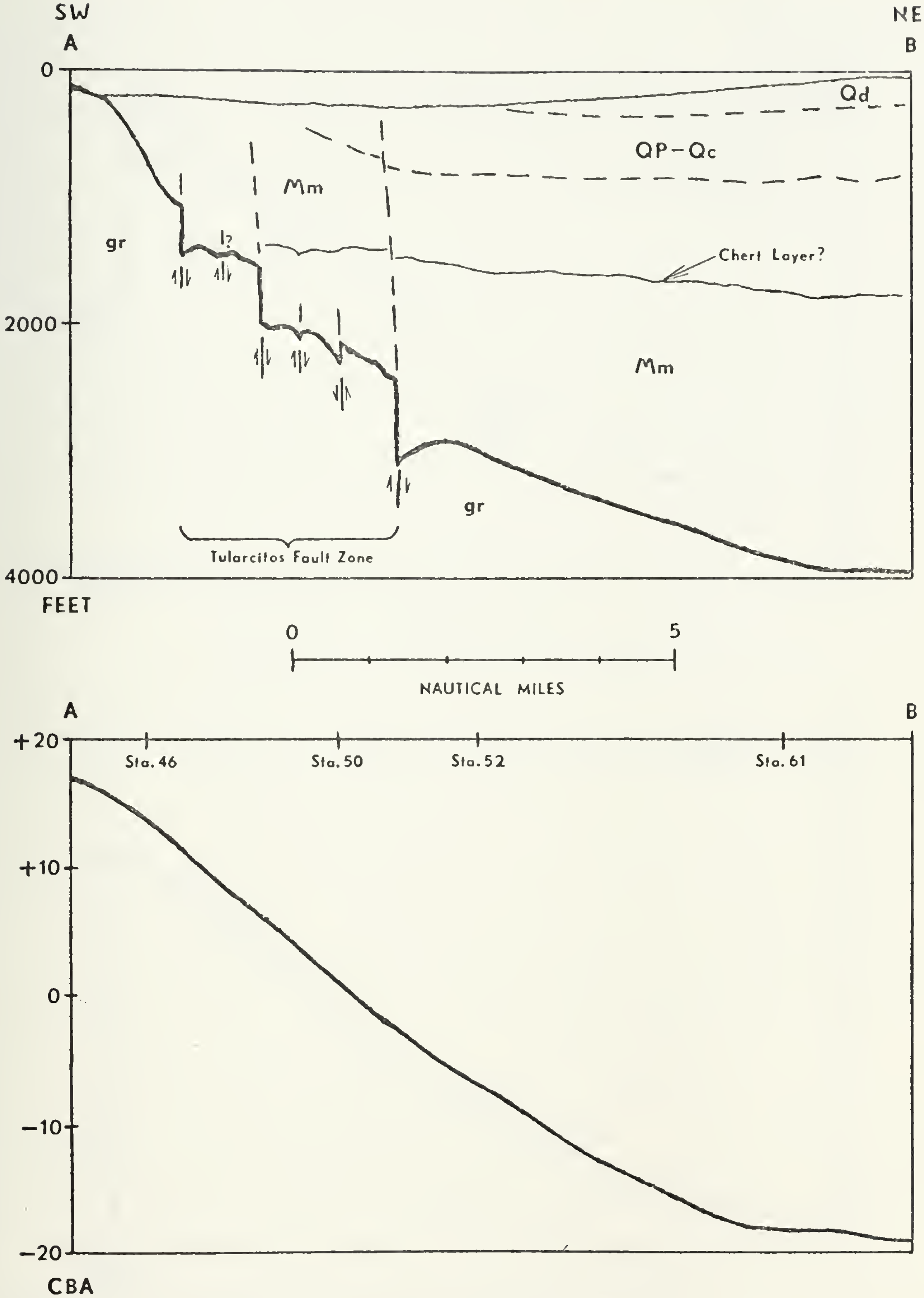


Figure 16. Comparison of CBA and Depth of Granite Substructure as Determined by Seismic Reflection for Profile A-B (Upper profile after Greene, 1970). The location of Profile A-B is shown in Figure 15.

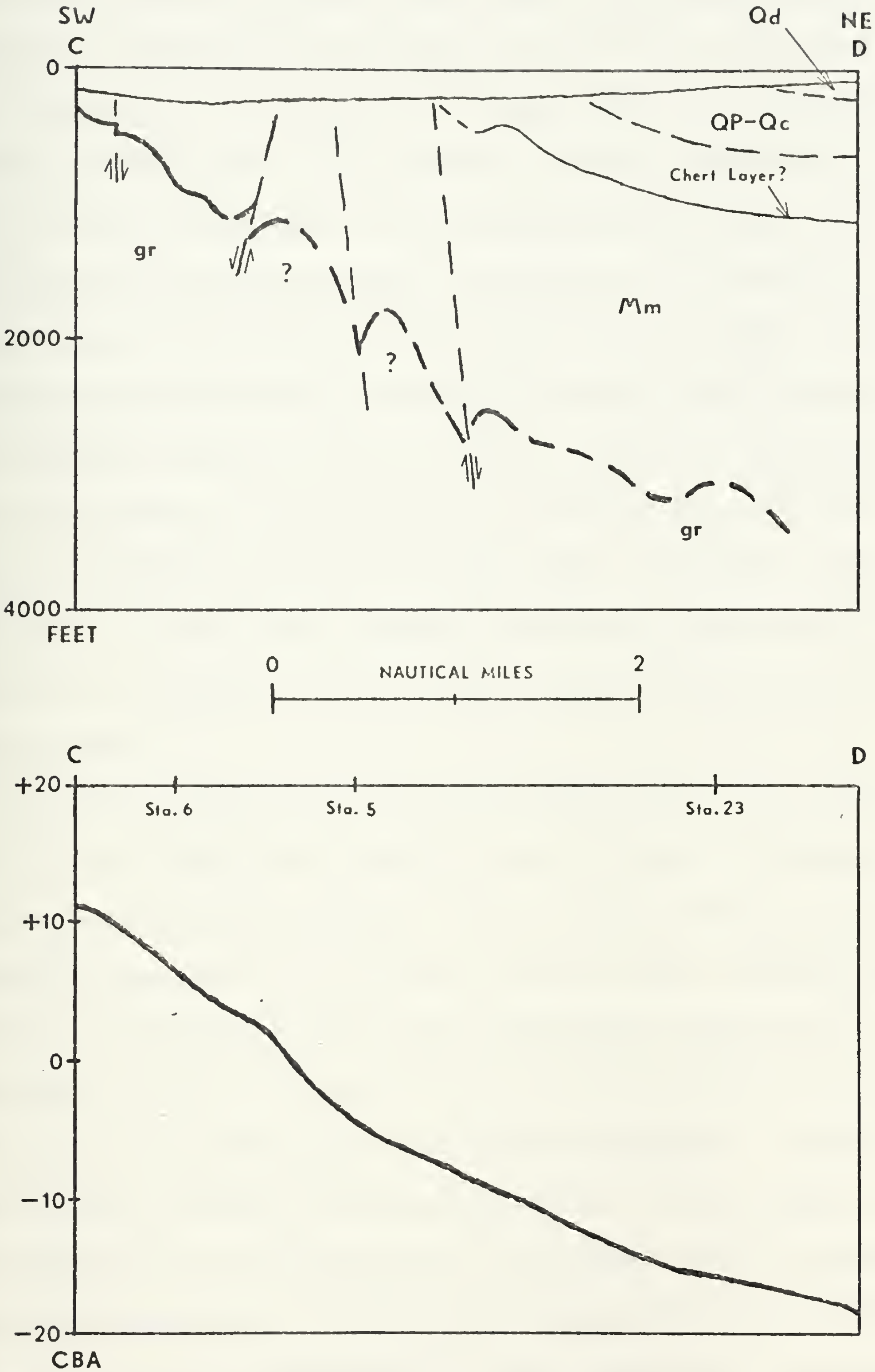


Figure 17. Comparison of CBA and Depth of Granite Substructure as Determined by Seismic Reflection for Profile C-D (Upper profile after Greene, 1970). The location of Profile C-D is shown in Figure 15.

difference between the two rock types. So doing permits equating a theoretical attraction of $2\pi G \rho_c h$ (where h is 520 ft and ρ_c is the density contrast) with the associated 5 mgal inferred value, and yields a density contrast of 0.75 g/cm^3. Since the slope of the igneous/sedimentary rock interface is fairly constant along the profile, the values of sublayer terrain irregularity corrections at two such locations will be close and their difference can therefore be neglected. This analysis assumes, then, that the relation between CBA and depth to basement is due solely to the magnitude of the density deficiency existing in the upper formation; the attraction at the point farther toward the northeast will be less since a thicker layer of the (lighter) Monterey Formation exists below.

A fairly accepted value for the density of the granodiorite is 2.75 g/cm^3, but the density of the in situ Monterey Formation is not accurately known. While this formation consists of multiple members, the Miocene marine shale predominates; its water-saturated density was determined experimentally by the author to be 1.85 g/cm^3 (true in situ density is higher since the lab samples were not under pressure). Sieck (1964) found the dry density of Monterey shale to vary from 1.41 to 2.10 g/cm^3, with an average of 1.80 g/cm^3, and his measured density of Monterey sandstone averaged 2.10 g/cm^3. Examination of various references to shale densities in general indicates that it is a highly variable figure (depending on age, location, and many other factors); values for diatomaceous

shales in the San Jauquin Valley are between 0.9 and 1.1 g/cm^3, while some water saturated shale types can be as dense as 3.21 g/cm^3 (Jakosky, 1950). In view of these many factors, the 2.00 g/cm^3 implied density of the Monterey Formation (2.75 g/cm^3 granodiorite minus the gravity survey's calculated 0.75 g/cm^3 density contrast) would appear quite acceptable as a true value.

Having arrived at densities of 2.00 and 2.75 g/cm^3 for the two major geological units in the area, it is now appropriate to consider the validity of using 2.67 g/cm^3 for the assumed average crustal Bouguer density. Since the Monterey Formation is less than 1 km thick, while the granodiorite substructure is probably several times thicker, the average crustal density in the vicinity of southern Monterey Bay is much closer to 2.75 than to 2.00 g/cm^3. Thus, while the frequently used average crustal density of 2.67 g/cm^3 can be unrealistic in many regions of the world, it is probably not the case here.

Throughout the course of this research it was anticipated that isoline positions over the deep Monterey Submarine Canyon could be inferred from the results of the bottom surveys in the northern and southern halves of Monterey Bay. Both sets of data were obtained with the same equipment in an identical manner and reduced in a comparable fashion, so there is no reason to doubt the validity of making such an inference. Figure 18 is the result of combining the data from Cronyn's (1973) survey with that of the author.

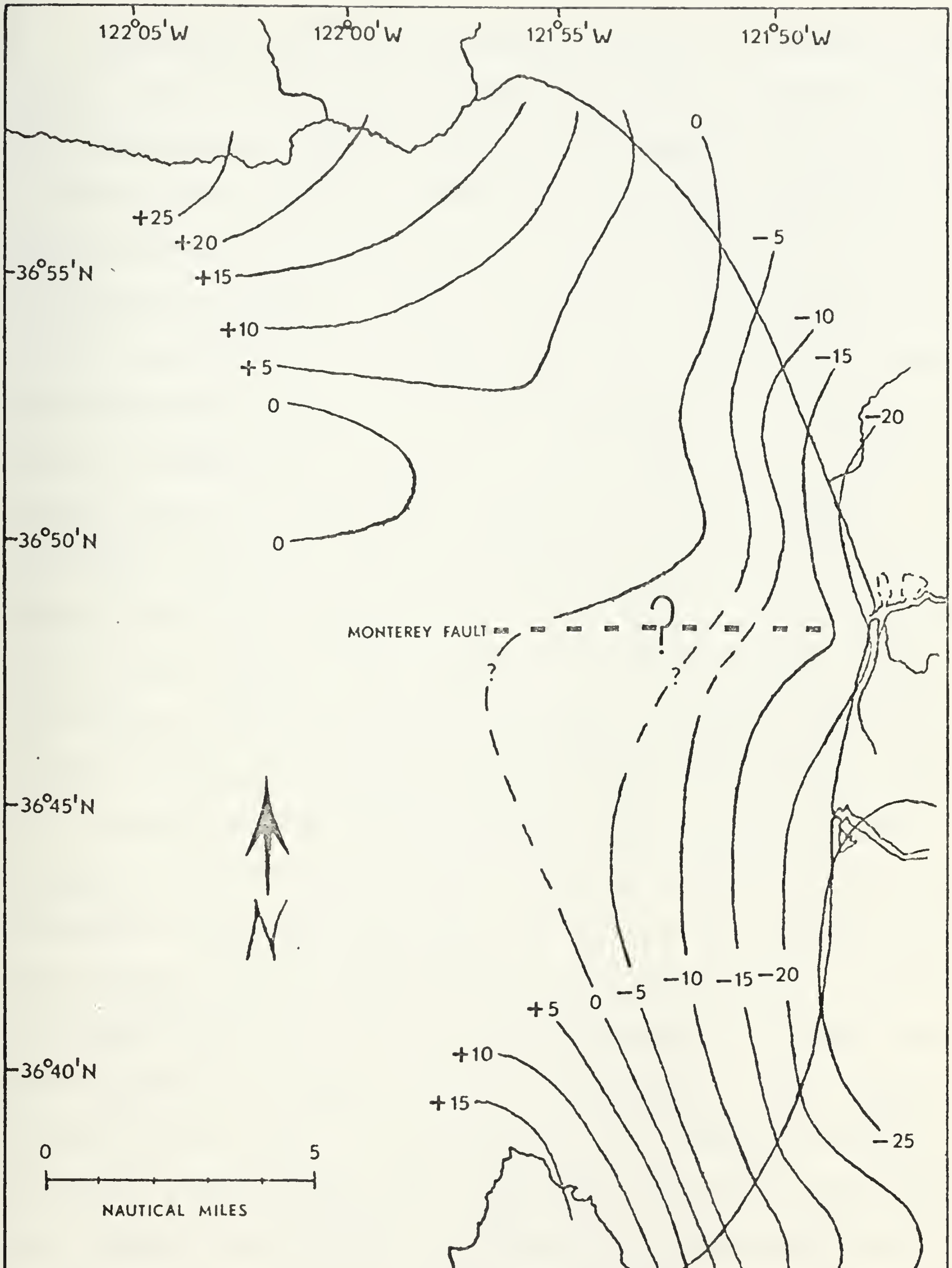
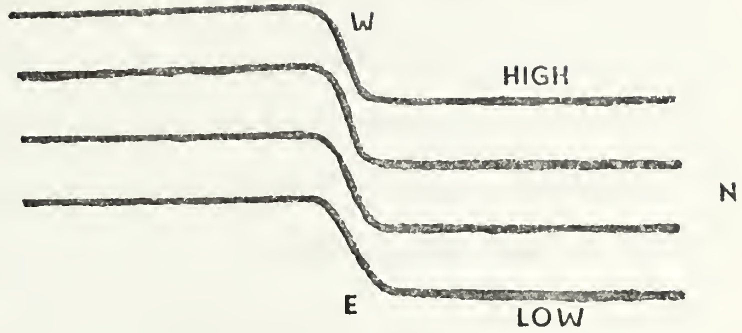


Figure 18. Composite Gravity Map of Monterey Bay (Northern Monterey Bay contours after Cronyn, 1973).

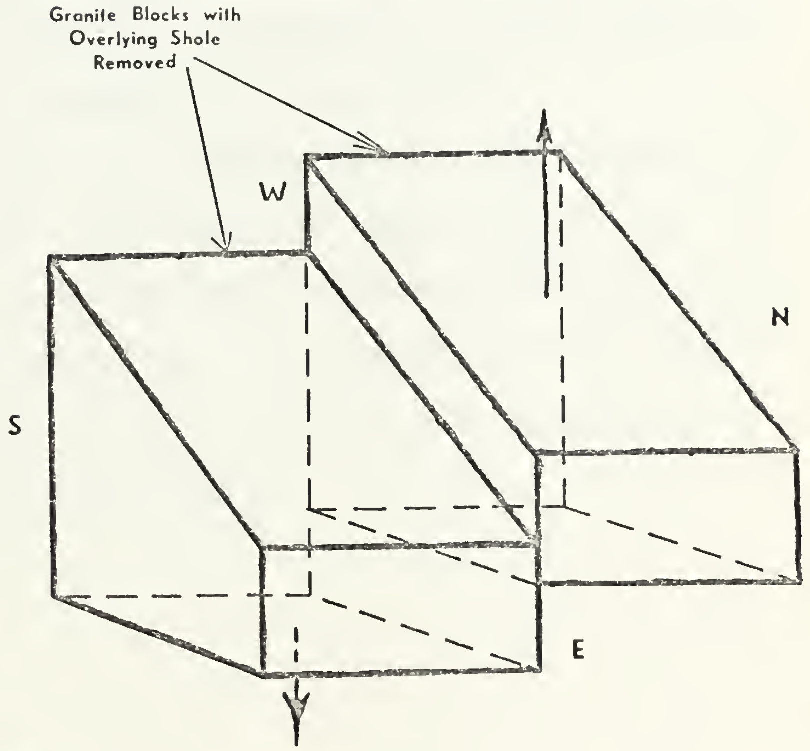
The fact that the southernmost positions of Cronyn's known 0,-5, -10, and -15 mgal isolines must bend to meet the northernmost positions of those of the author supports the theory that a fault exists along the axis of the Monterey Submarine Canyon. The difference in lithologies on opposite sides of the Canyon led Martin and Emery (1967) to recognize the so-called Monterey Fault parallel with the Canyon and offset at numerous locations by transverse faults of different magnitudes. Although the fault's suggested orientation is at an angle to the trend of almost all of the many fault zones in central California, the proposed situation is seen elsewhere, as in the case of the Santa Ynez Fault region north of Los Angeles, where the strike of the San Andreas Fault changes. Further evidence of the existence of the Monterey Fault based on seismic reflection tracks across the Canyon has been presented by Greene (1970).

Although some of the advocates of the Monterey Fault suggest that the motion along the fault is dip-slip with the northern side having descended relative to the southern side, this is not uniquely indicated by the gravity data. On both sides of the Canyon (in the eastern portion of the Bay) the CBA isolines run north-south with the higher values seaward (Fig. 18 and 19-A). If the motion of the Monterey Fault is, in fact, primarily dip-slip, the shape of the CBA field over the Canyon would suggest a relative motion such that the southern side has descended rather than the northern side, as shown in Figure 19-B. This is supported by the fact that the motion of the northeastern side of the Tularcitos Fault is

A. Inferred CBA Trend (Plan View)



B. Dip-Slip Fault Motion



C. Right-Lateral Strike-Slip Fault Motion

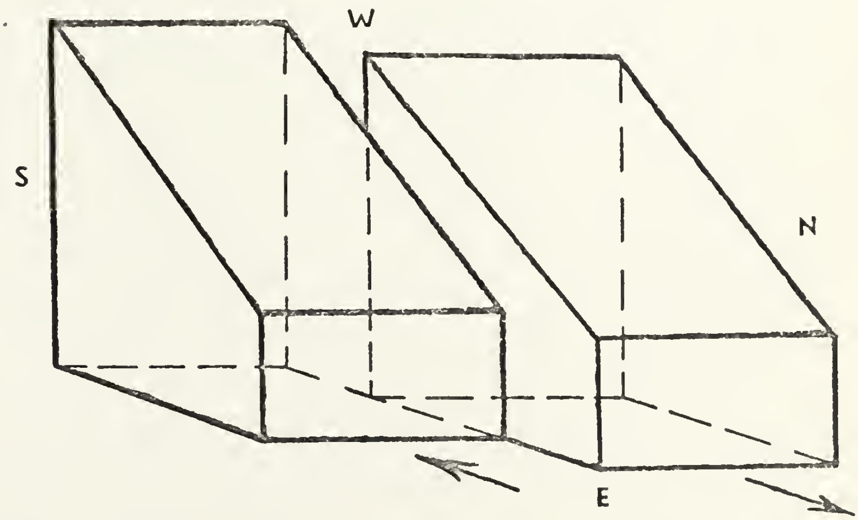


Figure 19. Two Possible Structural Explanations for the Inferred CBA Field in the Vicinity of the Monterey Submarine Canyon.

downward (Greene, 1970). If, on the other hand, the fault motion is primarily right-lateral strike-slip, the inferred CBA isolines over the Canyon may be explained as in Figure 19-C, wherein the northern side has moved east relative to the southern side. Specifying which of the two types of relative motion has occurred is not possible from the gravity information alone; quite possibly a combination of both types of motion has occurred, causing an oblique fault.

It may well be that the intersection of the Monterey Fault and the Palo Colorado - San Gregorio system farther to the west corresponds to the area where a concentration of recent seismic epicenters is located. More geophysical and oceanographic study of this region is needed before an accurate structural model can be developed.

VII. FUTURE WORK

It is recommended that CA-259 (the Monterey County Airport station) of the state gravity base station network be re-occupied in accordance with procedures outlined by Chapman (1966) to re-establish a correct value. Local construction there will be completed soon.

It is suggested that additional gravity measurements be made in the vicinity of the Monterey Submarine Canyon. Where a large portion of the coverage needed might be precluded (with a bottom gravimeter) by excessive depths and/or slopes, surface ship gravimetry could be called upon to complete this task. One such survey consisting of several canyon crossings was conducted by USGS in November, 1972, aboard the USNS BARTLETT, but at this writing the results are not yet available for inclusion here. They will eventually help greatly in removing the question marks in Figure 18.

At this writing the gravimeter and auxiliary equipment used for the Monterey Bay surveys is back aboard the R/V ACANIA. The author has thoroughly familiarized two new NPS students with the entire operation, and surveys are underway to extend shallow water coverage in two areas, one from Pt. Lobos to Pt. Sur and the other from Santa Cruz northwest to beyond Davenport. The goal of the project sponsors is to tie in these surveys with those conducted by the author and co-workers, so that a continuous picture of the off-shore Bouguer anomaly will become known. Hopefully this goal will be achieved.

APPENDIX A: SUPPLEMENTARY STATION INFORMATION

BOTTOM SURVEY

STATION	LATITUDE	LONGITUDE	G-OBSERVED	G-THEORET.
1	36 36 31	121 53 26	979895.028	979883.128
2	36 36 42	121 52 41	979892.293	979883.391
3	36 37 23	121 52 01	979885.315	979884.375
4	36 38 16	121 51 07	979876.674	979885.646
5	36 38 07	121 52 04	979885.502	979885.430
6	36 37 21	121 52 48	979894.019	979884.327
7	36 37 18	121 53 28	979899.353	979884.255
8	36 37 45	121 54 22	979898.428	979884.902
9	36 38 07	121 54 57	979899.686	979885.646
10	36 38 43	121 55 28	979903.752	979886.293
11	36 39 12	121 54 23	979904.074	979886.989
12	36 38 09	121 53 30	979901.069	979885.478
13	36 37 59	121 52 49	979896.036	979885.238
14	36 37 02	121 53 15	979897.034	979883.871
15	36 38 23	121 51 57	979884.889	979885.814
16	36 38 57	121 52 42	979893.832	979886.629
17	36 39 02	121 53 26	979898.615	979886.749
18	36 39 52	121 53 27	979896.275	979887.948
19	36 40 15	121 52 27	979889.308	979888.500
20	36 41 06	121 52 29	979890.660	979889.724
21	36 42 01	121 52 42	979892.480	979891.044
22	36 39 19	121 51 25	979881.520	979887.157
23	36 39 18	121 50 12	979872.588	979887.133
24	36 40 06	121 50 40	979877.537	979888.284
25	36 40 36	121 49 30	979870.061	979889.004
26	36 41 11	121 50 19	979877.662	979889.844
27	36 41 38	121 49 17	979870.289	979890.492
28	36 41 56	121 49 58	979876.333	979890.924
29	36 42 50	121 50 23	979878.629	979892.220
30	36 42 02	121 50 58	979883.215	979891.068
31	36 41 30	121 51 33	979886.657	979890.300
32	36 41 04	121 50 58	979881.988	979889.676
33	36 40 25	121 51 38	979884.754	979888.740
34	36 39 32	121 51 52	979886.064	979887.469
35	36 43 24	121 49 17	979872.276	979893.036
36	36 44 09	121 48 43	979871.901	979894.117
37	36 44 47	121 49 17	979875.478	979895.029
38	36 45 29	121 48 46	979876.404	979896.038
39	36 41 22	121 53 13	979895.163	979890.108
40	36 41 04	121 53 48	979897.076	979889.676
41	36 40 34	121 53 24	979894.934	979888.956
42	36 40 02	121 54 34	979903.294	979888.188
43	36 39 35	121 55 30	979907.755	979887.541
44	36 39 03	121 56 10	979910.033	979886.773
45	36 38 49	121 56 54	979908.982	979886.432

STATION	LATITUDE	LONGITUDE	G-OBSERVED	G-THEORET.
46	36 39 34	121 56 46	979910.948	979887.517
47	36 39 51	121 56 40	979910.417	979887.925
48	36 40 34	121 55 25	979906.144	979888.956
49	36 38 21	121 54 16	979903.845	979885.766
50	36 41 28	121 54 36	979901.714	979890.252
51	36 42 05	121 53 42	979898.698	979891.140
52	36 42 50	121 53 00	979894.528	979892.220
53	36 42 36	121 51 54	979889.433	979891.884
54	36 43 15	121 51 55	979889.267	979892.820
55	36 43 36	121 50 51	979882.560	979893.324
56	36 42 44	121 49 14	979871.423	979892.076
57	36 44 04	121 49 50	979875.478	979893.997
58	36 44 30	121 50 47	979883.371	979894.621
59	36 45 11	121 50 29	979882.851	979895.605
60	36 46 46	121 49 21	979885.960	979897.887
61	36 45 44	121 49 32	979879.721	979896.398
62	36 46 19	121 48 47	979878.671	979897.238
63	36 46 57	121 48 10	979878.671	979898.151
64	36 47 50	121 47 47	979879.908	979899.424
65	36 48 10	121 48 27	979904.709	979899.905
66	36 47 23	121 49 02	979886.293	979898.776
67	36 46 12	121 50 34	979886.906	979897.070
68	36 45 16	121 51 36	979891.118	979895.725
69	36 44 32	121 51 52	979891.575	979894.669
70	36 43 50	121 51 32	979887.156	979893.660
71	36 43 38	121 52 30	979892.605	979893.372
72	36 44 26	121 52 56	979897.024	979894.525
73	36 45 55	121 51 48	979894.830	979896.662
74	36 46 51	121 50 36	979890.567	979898.007
75	36 46 46	121 51 42	979897.211	979897.887
76	36 45 28	121 52 40	979898.511	979896.014
77	36 44 58	121 53 45	979901.672	979895.293
78	36 44 00	121 53 39	979898.553	979893.900
79	36 43 27	121 54 25	979902.182	979893.108
80	36 43 18	121 53 30	979897.086	979892.892
81	36 42 38	121 54 08	979897.232	979891.932
82	36 37 34	121 50 58	979875.343	979884.638

STATION	F.T.	DEPTH	FAC	BC	TC	CC
1	0.02	40.0	-3.841	1.918	2.98	-0.018
2	0.00	75.1	-7.118	3.566	2.82	-0.034
3	-0.01	93.4	-8.832	4.428	2.69	-0.041
4	-0.01	84.2	-7.944	3.985	2.58	-0.038
5	-0.02	151.9	-14.309	7.181	2.65	-0.067
6	-0.02	138.1	-12.986	6.520	2.77	-0.060
7	-0.02	134.5	-12.606	6.336	2.90	-0.060
8	-0.02	79.7	-7.430	3.740	3.00	-0.035
9	-0.02	76.0	-7.054	3.555	3.12	-0.034
10	-0.02	130.4	-12.166	6.122	3.23	-0.059
11	-0.02	256.7	-24.025	12.079	2.93	-0.116
12	-0.02	212.9	-19.885	10.003	2.86	-0.096
13	-0.02	189.9	-17.710	8.913	2.76	-0.085
14	-0.02	108.6	-10.050	5.069	2.90	-0.048
15	-0.01	165.2	-15.347	7.732	2.62	-0.073
16	0.00	214.1	-19.937	10.037	2.69	-0.096
17	0.00	244.9	-22.841	11.495	2.79	-0.110
18	0.01	254.6	-23.744	11.950	2.78	-0.115
19	0.01	235.2	-21.921	11.034	2.58	-0.106
20	0.01	248.2	-23.162	11.655	2.53	-0.112
21	0.01	252.6	-23.577	11.862	2.48	-0.114
22	-0.02	156.5	-14.705	7.386	2.55	-0.068
23	-0.01	76.6	-7.178	3.608	2.44	-0.034
24	0.00	142.3	-13.347	6.706	2.38	-0.063
25	0.01	71.5	-6.681	3.361	2.30	-0.031
26	0.02	145.1	-13.596	6.834	2.29	-0.064
27	0.03	78.1	-7.288	3.667	2.13	-0.034
28	0.03	131.4	-12.297	6.183	2.14	-0.059
29	0.04	140.4	-13.147	6.609	2.15	-0.062
30	0.04	191.0	-17.905	8.998	2.30	-0.085
31	0.05	221.3	-20.768	10.434	2.35	-0.100
32	0.06	186.3	-17.490	8.786	2.34	-0.084
33	0.06	204.8	-19.228	9.659	2.46	-0.091
34	0.07	193.9	-18.209	9.146	2.57	-0.086
35	0.06	67.0	-6.329	3.174	1.95	-0.030
36	0.06	39.1	-3.707	1.857	1.90	-0.017
37	0.05	54.4	-5.158	2.585	1.91	-0.024
38	0.05	42.7	-4.050	2.028	1.85	-0.018
39	0.02	264.1	-24.870	12.483	2.57	-0.119
40	0.02	275.1	-25.897	12.999	2.75	-0.124
41	0.02	257.8	-24.258	12.178	2.71	-0.116
42	0.01	276.4	-26.001	13.054	2.94	-0.125
43	0.01	271.9	-25.564	12.836	3.27	-0.124
44	0.00	231.8	-21.781	10.938	3.52	-0.105
45	0.00	204.7	-19.232	9.658	3.73	-0.091

STATION	E.T.	DEPTH	FAC	BC	TC	CC
46	0.00	270.1	-25.369	12.743	3.62	-0.122
47	0.00	302.2	-28.380	14.255	3.59	-0.137
48	0.00	293.6	-27.550	13.841	3.28	-0.133
49	-0.01	211.1	-19.767	9.936	2.96	-0.095
50	0.11	294.7	-27.661	13.896	2.96	-0.133
51	0.10	278.7	-26.162	13.143	2.69	-0.126
52	0.10	258.8	-24.295	12.205	2.43	-0.118
53	0.10	228.5	-21.442	10.772	2.37	-0.102
54	0.09	217.1	-20.370	10.234	2.25	-0.098
55	0.09	155.2	-14.547	7.310	2.15	-0.070
56	0.08	75.7	-7.072	3.557	2.04	-0.034
57	0.07	76.8	-7.172	3.609	2.02	-0.035
58	0.06	147.9	-13.847	6.961	2.10	-0.066
59	0.05	125.3	-11.708	5.889	2.03	-0.056
60	0.04	136.5	-12.757	6.416	1.94	-0.061
61	0.04	72.3	-6.707	3.380	1.89	-0.033
62	0.03	49.8	-4.583	2.315	1.83	-0.022
63	0.02	33.0	-2.987	1.515	1.77	-0.015
64	0.01	37.0	-3.352	1.701	1.78	-0.017
65	-0.01	456.8	-42.794	21.509	2.98	-0.212
66	-0.02	135.4	-12.552	6.328	2.19	-0.060
67	-0.03	153.0	-14.194	7.154	2.09	-0.069
68	-0.04	208.4	-19.399	9.768	2.20	-0.093
69	-0.04	219.5	-20.425	10.285	2.20	-0.099
70	-0.05	194.7	-18.084	9.111	2.25	-0.088
71	-0.05	241.8	-22.507	11.333	2.35	-0.109
72	-0.05	261.3	-24.337	12.253	2.38	-0.119
73	-0.06	241.2	-22.447	11.304	2.29	-0.109
74	-0.06	185.3	-17.188	8.664	2.27	-0.083
75	-0.06	263.9	-24.576	12.373	2.50	-0.119
76	-0.06	269.9	-25.150	12.660	2.40	-0.122
77	-0.06	294.6	-27.475	13.827	2.59	-0.133
78	-0.06	279.7	-26.077	13.125	2.52	-0.128
79	-0.06	300.9	-28.078	14.129	2.76	-0.136
80	-0.06	277.7	-25.891	13.031	2.54	-0.126
81	-0.06	290.1	-27.076	13.623	2.79	-0.131
82	-0.06	52.4	-4.746	2.408	2.63	-0.024

APPENDIX A (Continued)

SHORELINE SURVEY

Station	Latitude ° ' "	Longitude ° ' "	Observed Gravity	Theoretical Gravity
A	36 36 34	121 57 24	979900.880	979883.200
B	36 37 09	121 56 26	979899.280	979884.039
C	36 38 15	121 56 05	979898.380	979885.622
D	36 36 57	121 53 55	979893.790	979883.751
E	36 36 32	121 53 24	979891.700	979883.152
F	36 36 16	121 52 12	979887.600	979882.768
G	36 39 45	121 49 18	979863.740	979887.781
H	36 41 57	121 48 32	979863.050	979890.948
I	36 44 53	121 47 57	979869.880	979895.173
J	36 48 28	121 47 21	979876.420	979900.337

Station	Elevation	Earth Tide	FAC	BC	TC
A	3.2'	+0.13	0.301	0.109	3.84
B	0.6'	+0.06	0.056	0.020	3.81
C	0.1'	+0.07	0.009	0.003	3.78
D	8.2'	+0.08	0.771	0.280	3.21
E	7.5'	+0.09	0.705	0.257	3.32
F	1.1'	+0.04	0.103	0.038	2.84
G	5.1'	+0.09	0.480	0.174	2.50
H	2.3'	+0.02	0.216	0.078	2.12
I	1.0'	+0.12	0.094	0.034	2.09
J	6.9'	+0.13	0.649	0.235	1.97

COMPUTER PROGRAM FOR SHORELINE STATIONS

```
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION THEO(10),ELEV(10),FAC(10),FAA(10),BC(10),SBA
     1(10),CBA(10),TLA(10),ARGA(10),ARGB(10),DEGREE(10),GOB(
     110),ET(10),TC(10)
      READ (5,500) (GOB(I),I=1,10)
      READ (5,1000) (DEGREE(I),I=1,10)
      READ (5,2000) (ELEV(I),I=1,10)
      READ (5,3000) (ET(I),I=1,10)
      READ (5,3500) (TC(I),I=1,10)
  500 FORMAT(8F10.3)
 1000 FORMAT(8F10.7)
 2000 FORMAT(10F3.1)
 3000 FORMAT(10F4.2)
 3500 FORMAT(10F4.2)
      DO 4000 I=1,10
      TLA(I)=3.14159D0*(DEGREE(I)/180.0D0)
      ARGA(I)=DSIN(TLA(I))
      ARGB(I)=DSIN(2.0D0*TLA(I))
      THEO(I)=978049.0D0*(1.0D0+(0.0052884D0*((ARGA(I))**2))
     1-0.0000059D0*((ARGB(I))**2))
      FAC(I)=0.09406D0*(ELEV(I))
      FAA(I)=GOB(I)-THEO(I)+ET(I)+FAC(I)
      BC(I)=(2.0D0*3.14159D0*6.67D0*30.48D0*2.67D0*(ELEV(I))
     1)/100000.0D0
      SBA(I)=FAA(I)-BC(I)
 4000 CBA(I)=SBA(I)+TC(I)
      DO 5000 I=1,10
      WRITE (6,6000) I,GOB(I),THEO(I),ET(I),ELEV(I),FAC(I),F
     1AA(I),BC(I),SBA(I),TC(I),CBA(I)
 5000 CONTINUE
 6000 FORMAT(///,20X,I2,3X,F10.3,3X,F10.3,3X,F4.2,3X,F3.1,3X
     1,F6.3,3X,F7.3,3X,F6.3,3X,F7.3,3X,F4.2,3X,F7.3)
      STOP
      END
```

COMPUTER PROGRAM FOR UNDERWATER STATIONS

```
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION DATE(90),GMT(90),LATDEG(90),LONDEG(90),LATMI
     1N(90),LATSEC(90),LONMIN(90),LONSEC(90),COUNTR(90),GREL
     1(90),VALGRV(90),TERCOR(90),BUGA(90),GVTIDE(90),BUGAET(
     190),DECK(90),BOTT(90),DIFF(90),DEPTH(90),TIDEHT(90),FA
     1C(90),FAA(90),BC(90),SBA(90),DEGREE(90),TLA(90),ARGA(9
     10),ARGB(90),THEO(90),CURV(90),CBA(90),TFAC(90),TFAA(90
     1)
      READ (5,500) (DATE(I),I=1,82)
      READ (5,501) (GMT(I),I=1,82)
      READ (5,1000) (COUNTR(I),I=1,82)
      READ (5,1200) (LATMIN(I),I=1,82)
      READ (5,1201) (LATSEC(I),I=1,82)
      READ (5,1202) (LONMIN(I),I=1,82)
      READ (5,1203) (LONSEC(I),I=1,82)
      READ (5,2500) (DEGREE(I),I=1,82)
      READ (5,4444) (GVTIDE(I),I=1,82)
      READ (5,7000) (DECK(I),I=1,82)
      READ (5,7001) (BOTT(I), I=1,82)
      READ (5,7004) (TIDEHT(I),I=1,82)
      READ (5,7005) (TERCOR(I),I=1,82)
      READ (5,7006) (CURV(I),I=1,82)
  500 FORMAT(20A4)
  501 FORMAT(20A4)
 1000 FORMAT(11F7.2,3X)
 1200 FORMAT(40A2)
 1201 FORMAT(40A2)
 1202 FORMAT(40A2)
 1203 FORMAT(40A2)
 2500 FORMAT(8F10.7)
 4444 FORMAT(20F4.2)
 7000 FORMAT(20F4.1)
 7001 FORMAT(16F5.1)
 7004 FORMAT(20F4.1)
 7005 FORMAT(20F4.2)
 7006 FORMAT(16F5.3)
      DO 7500 I=1,82
      LATDEG(I)=36
      LONDEG(I)=121
      TLA(I)=3.14159D0*(DEGREE(I)/180.0D0)
      ARGA(I)=DSIN(TLA(I))
      ARGB(I)=DSIN(2.0D0*TLA(I))
      THEO(I)=978049.0D0*(1.0D0+(0.0052884D0*((ARGA(I))**2))
     1-0.0000059D0*((ARGB(I))**2))
      VALGRV(I)=979891.70D0+((COUNTR(I)-3323.050D0)*1.039850
     1D0)
      BUGA(I)=VALGRV(I)-THEO(I)
      BUGAET(I)=BUGA(I)+GVTIDE(I)
      DIFF(I)=BOTT(I)-DECK(I)
      DEPTH(I)=0.770D0*DIFF(I)
      FAC(I)=-0.094060D0*(DEPTH(I)-TIDEHT(I))
      FAA(I)=BUGAET(I)+FAC(I)
      TFAC(I)=-0.09406D0*(DEPTH(I)-TIDEHT(I))+2.0D0*3.14159D
     10*6.67D0*1.027D0*30.48D0*DEPTH(I)/100000.0D0+2.0D0*3.1
     14159D0*6.67D0*1.027D0*30.48D0*(DEPTH(I)-TIDEHT(I))/100
     1000.0D0
      TFAA(I)=BUGAET(I)+TFAC(I)
      BC(I)=((2.0D0*3.14159D0*6.67D0*1.027D0*30.48D0*DEPTH(I
     1))/100000.0D0)+((2.0D0*3.14159D0*6.67D0*2.67D0*30.48D0
     1*(DEPTH(I)-TIDEHT(I)))/100000.0D0)
      SBA(I)=FAA(I)+BC(I)
      IF(GVTIDE(I).EQ.0.0) GVTIDE(I)=1.E-10
 7500 CBA(I)=SBA(I)+TERCOR(I)+CURV(I)
      STOP
      END
```

(OUTPUT FORMAT STATEMENTS HAVE BEEN OMITTED.)

REFERENCES CITED

1. Beyer, L. A., R. E. Von Huene, T. H. McCulloh, and J. R. Lovett. 1966. Measuring Gravity on the Sea Floor in Deep Water. J. Geophys. Res. 71(8): 2091-2100.

2. Bishop, C. C. and R. H. Chapman. 1967. Bouguer Gravity Map of California (Santa Cruz Sheet). California Division of Mines and Geology, San Francisco.

3. Bullard, E. C. 1936. Gravity Measurements in East Africa. Phil. Trans. Roy. Soc. (London). Ser. A, 235(757): 445-531.

4. Chapman, R. H. 1966. The California Division of Mines and Geology Gravity Base Station Network (CDMG Spec. Rpt. No. 90). California Office of State Printing, San Francisco. 49 p.

5. Cronyn, B. C. 1973. An Underwater Gravity Survey and Investigation of Northern Monterey Bay. M. S. Thesis, U. S. Naval Postgraduate School, Monterey, Ca. (Unpublished report)

6. Dobrin, M. B. 1960. Introduction to Geophysical Prospecting, 2nd Ed. McGraw-Hill Book Co., Inc., New York. 446 p.

7. Fairborn, J. W. 1963. Gravity Survey and Interpretation of the Northern Portion of the Salinas Valley. Student Report, Stanford University, Palo Alto, Ca. 21 p. (Unpublished report)

8. Grant, F. S., and G. F. West. 1965. Interpretation Theory in Applied Geophysics. McGraw-Hill Book Co., Inc., San Francisco. 583 p.

9. Greene, H. G. 1970. Geology of Southern Monterey Bay and Its Relationship to the Ground Water Basin and Salt Water Intrusion. Open-file Report, USGS, Menlo Park, Ca. 50 p. (Unpublished report)

10. Hayford, J. F., and W. Bowie. 1912. The Effect of Topography and Isostatic Compensation Upon the Intensity of Gravity (U. S. C. & G. S. Spec. Pub. No. 10). U. S. Government Printing Office, Washington, D. C. 132 p.

11. Heiskanen, W. A., and F. A. Vening Meinesz. 1958. The Earth and Its Gravity Field. McGraw-Hill Book Co., Inc., New York. 470 p.

12. Ivey, C. G. 1969. A Gravity Survey of Fort Ord, California. M. S. Thesis, U. S. Naval Postgraduate School, Monterey, Ca. 55 p. (Unpublished report)

13. Jakosky, J. J. 1950. Exploration Geophysics (2nd Ed.). Trija Publishing Co., Newport Beach, Ca. 1195 p.

14. LaCoste, L. J. B. 1934. A New Type Long Period Vertical Seismograph. Physics 5: 178-180.

15. LaCoste, L. J. B. 1967. Measurement of Gravity at Sea and in the Air. Rev. Geophys. 5(4): 447-526.

16. LaCoste and Romberg Operating and Repair Manual, Models HD and HG Underwater Gravimeters. LaCoste and Romberg, Inc. Austin, Tex. (Unpublished report)

17. Martin, B. D. 1964. Monterey Submarine Canyon, California: Genesis and Relationship to Continental Geology. PhD Dissertation, University of Southern California, Los Angeles. 249 p. (Unpublished report)

18. Martin, B. D. and K. O. Emery. 1967. Geology of Monterey Submarine Canyon, California. Am. Assoc. Petrol. Geol. Bull. 51(11): 2281-2304.

19. Sieck, H. C. 1964. A Gravity Investigation of the Monterey-Salinas Area. Student Report, Stanford University, Palo Alto, Ca. 40 p. (Unpublished report)

20. Shepard, F. P. 1948. Investigation of Head of Monterey Submarine Canyon. Scripps Inst. Oceanogr. Submarine Geology Report No. 1, 15 p.

21. Souto, A. P. D. A Bottom Gravity Survey of Carmel Bay, California. M. S. Thesis, U. S. Naval Postgraduate School, Monterey, Ca. (Unpublished report)

22. Swick, C. H. 1942. Pendulum Gravity Measurements and Isostatic Reductions (U. S. C. & G. S. Spec. Pub. No. 232). U. S. Government Printing Office, Washington, D. C. 82 p.

23. U. S. Department of Commerce, 1972. Tide Tables, High and Low Water Predictions, 1972, West Coast North and South America including the Hawaiian Islands. U. S. Government Printing Office, Washington, D. C. 226 p.

24. Woollard, G. P., and J. C. Rose. 1963. International Gravity Measurements. George Banta Co., Inc., Menasha, Wisc. 518 p.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0212 Naval Postgraduate School Monterey, California 93940	2
3.	Department of Oceanography Naval Postgraduate School Monterey, California 93940	3
4.	Oceanographer of the Navy The Madison Building 732 North Washington Street Alexandria, Virginia 22314	1
5.	Office of Naval Research Code 480-D Arlington, Virginia 22217	1
6.	Professor Robert S. Andrews Department of Oceanography, Code 58Ad Naval Postgraduate School Monterey, California 93940	10
7.	Professor Joseph J. von Schwind Department of Oceanography, Code 58Vs Naval Postgraduate School Monterey, California 93940	3
8.	Lieutenant Robert A. Brooks, USN SMC 2820 Naval Postgraduate School Monterey, California 93940	3
9.	Dr. Francis P. Shepard Scripps Institute of Oceanography La Jolla, California 92037	1
10.	Dr. Rodger H. Chapman Division of Mines and Geology Resources Building, Room 1341 1416 Ninth Street Sacremento, California 95814	1

	No. Copies
11. Dr. Howard Oliver United States Geological Survey 345 Middlefield Road Menlo Park, California 94025	1
12. Dr. S. L. Robbins United States Geological Survey 345 Middlefield Road Menlo Park, California 94025	1
13. Mr. H. Gary Greene United States Geological Survey 345 Middlefield Road Menlo Park, California 94025	1
14. Gravity Section Naval Oceanographic Office Washington, D. C. 20390	1
15. Mr. H. B. Parks LaCoste and Romberg, Inc. 6606 North Lamar Austin, Texas 78752	1
16. Professor Warren Thompson Department of Oceanography, Code 58 Th Naval Postgraduate School Monterey, California 93940	1
17. Master, R/V ACANIA Department of Oceanography Naval Postgraduate School Monterey, California 93940	1
18. Lieutenant Commander Antonio P. D. Souto Av. D. Luis I-8 R/C ESQ. Alfragide, Portugal	1
19. Lieutenant Brian S. Cronyn, USN USS INDEPENDENCE (CVA-62) Fleet Post Office New York, New York 09501	1

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

INATING ACTIVITY (Corporate author) val Postgraduate School nterey, California 93940	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

ORT TITLE

A Bottom Gravity Survey of the Shallow Water Regions of Southern Monterey Bay and Its Geological Interpretation

RIPTIVE NOTES (Type of report and, inclusive dates)

Master's Thesis; March 1973

HOR(S) (First name, middle initial, last name)

obert Andrew Brooks, Sr.

ORT DATE March 1973	7a. TOTAL NO. OF PAGES 92	7b. NO. OF REFS 24

TRACT OR GRANT NO. JECT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

TRIBUTION STATEMENT

Approved for public release; distribution unlimited.

PLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Naval Postgraduate School Monterey, California 93940

TRACT

Eighty-two ocean bottom gravity stations in southern Monterey y were occupied in the summer and fall of 1972 from the R/V ANIA. A land gravity survey of ten stations about the perimeter the Bay was conducted in the spring of 1972. Gravimeters ployed were LaCoste and Romberg Models H6G and G-17B, respectively.

Conventional steps in data reduction are discussed, and a rrain correction theory unique to ocean bottom gravimetry is esented. The complete Bouguer anomaly (CBA) field for bottom and oreline surveys is included.

The geological interpretation of the gravity data is discussed iefly. Sub-bottom structure of southern Monterey Bay as termined by seismic reflection is verified by the CBA field, d a calculated density contrast between the basement granodiorite d overlying sedimentary strata is found to be realistic. The ta supports the existence of a fault oriented beneath the nterey Submarine Canyon.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
OLOGY						
OPHYSICS						
AVITY						
RINE GEOLOGY						
UTHERN MONTEREY BAY						

Brooks

A bottom gravity survey of the shallow water regions of southern Monterey Bay and its geological interpretation.